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# SPECIFICATION.

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT WE, NAOTO JIKUTANI, a citizen of Japan residing at Miyagi, Japan, SHUNICHI SATO, a citizen of Japan residing at Miyagi, Japan and TAKASHI TAKAHASHI, a citizen of Japan residing at Miyagi, Japan have invented certain new and useful improvements in

LASER DIODE HAVING AN ACTIVE LAYER CONTAINING N AND  
OPERABLE IN A 0.6 $\mu$ m WAVELENGTH BAND

of which the following is a specification:-

1     BACKGROUND OF THE INVENTION

          The present invention is a continuation-in-part application of the United States patent application 09/289,955 filed April 13, 1999.

5           The present invention generally relates to optical semiconductor devices and more particularly to an optical semiconductor device including a laser diode operable in a 0.6  $\mu\text{m}$  wavelength band.

          The optical wavelength band of 0.6  $\mu\text{m}$  is used  
10           extensively in storage devices such as an optical disk drive or a magneto-optical disk drive for optical writing or reading of information. Further, the optical wavelength band of 0.6  $\mu\text{m}$  is important in optical telecommunication that is conducted by using plastic  
15           optical fibers.

          Thus, intensive investigations are being made in relation to a laser diode of an AlGaInP system that produces an output optical beam with the optical wavelength band of 0.6  $\mu\text{m}$ . The laser diode using the  
20           AlGaInP system is also important in color display devices as an optical source of red to green colors. It should be noted that the AlGaInP system is a III-V material providing the largest bandgap (2.3 eV or 540 nm wavelength) while simultaneously maintaining a lattice  
25           matching with a GaAs substrate.

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1           On the other hand, such a laser diode using  
the AlGaInP system for the active layer thereof suffers  
from the problem of poor confinement of carriers,  
particularly electrons, in the active layer. More  
5 specifically, carriers escape easily from the active  
layer to adjacent upper and/or lower cladding layers due  
to the small band discontinuity formed at the  
heterojunction interface between the AlGaInP active  
layer and the adjacent cladding layers. Associated with  
10 such a small band discontinuity and resultant weak  
carrier confinement, the conventional AlGaInP laser  
diodes have suffered from the problem of large  
temperature dependence for the threshold characteristic  
of the laser oscillation. This problem of poor  
15 temperature characteristic of the laser diode is  
pronounced further when the bandgap of the active layer  
is increased for decreasing the laser oscillation  
wavelength by using a quantum well structure for the  
active layer.

20           In order to avoid the problem of overflowing  
of the carriers away from the active layer, the Japanese  
Laid-Open Patent Publication 4-114486 describes the use  
of a multiple quantum barrier (MQB) structure for the  
carrier blocking layer. Further, Hamada, H. et al.,  
25 Electronics Letters, vol.28, no.19, 10th September 1992,

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1 pp.1834-1836, describes the use of a strained MQW  
structure strained with a compressive stress. According  
to Hamada et al., op. cit., a continuous laser  
oscillation with a wavelength of as small as 615 nm is  
5 achieved by forming the strained MQW structure by using  
a quantum well layer having a composition of  
(Al<sub>0.08</sub>Ga<sub>0.92</sub>)<sub>0.45</sub>In<sub>0.55</sub>As in combination with a barrier  
layer and a GaAs substrate. However, the laser diode of  
thus produced has an unsatisfactory temperature  
10 characteristic, indicating that the desired, effective  
confinement of carriers is not realized.

Further, there is another proposal of a laser  
diode operable in the 600 nm wavelength band by using  
the material system of AlGaInP in combination with a  
15 substrate other than GaAs. For example, the Japanese  
Laid-Open Patent Publication 6-53602 proposes the use of  
an MQW structure including GaInP quantum well layers and  
GaInP barrier layers for the active layer in combination  
with a GaP substrate and AlGaP cladding layers. The  
20 foregoing reference further teaches the use of N as an  
impurity element forming an isoelectronic trap. This  
device, however, cannot provide the satisfactory  
confinement of carriers in the active layer. Thereby,  
the laser diode is characterized by a poor temperature  
25 characteristic.

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Unfortunately, such a III-V material system containing N generally shows a severe bowing in the bandgap due to the large electronegativity of N, and the desired increase of the bandgap is not achieved in the foregoing lattice matching composition, contrary to the prediction of the foregoing Japanese Laid-Open Patent Publication 7-7223. Further, in view of the existence of extensive immiscibility gap in the III-V material system containing N, formation of a III-V crystal containing such a large amount of N is not possible even when a non-equilibrium growth process such as MBE process or MOCVD process is used.

1           Thus, it has been difficult to achieve the  
laser oscillation at the 600 nm wavelength band even  
when other material systems are used. The use of the  
AlGaInP system, on the other hand, cannot provide the  
5   desired efficient confinement of carriers in the active  
layer due to the insufficient band discontinuity at the  
heterojunction interface between the active layer and  
the cladding layer.

10   SUMMARY OF THE INVENTION

Accordingly, it is a general object of the  
present invention to provide a novel and useful laser  
diode operable in the 600 nm wavelength band wherein the  
problems are eliminated.

15           Another and more specific object of the  
present invention to provide a laser diode operable in  
the 600 nm wavelength band with effective confinement of  
carriers in the active layer of the laser diode.

Another object of the present invention is to  
20   provide a laser diode, comprising:

          a substrate of a first conductivity type;

          a first cladding layer having said first  
conductivity type, said first cladding layer being  
formed on said substrate epitaxially;

25           an active layer of a group III-V compound

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1 semiconductor material formed epitaxially on said first  
cladding layer;

a second cladding layer having a second,  
opposite conductivity type, said second cladding layer  
5 being formed on said active layer epitaxially;

a first electrode injecting first type  
carriers having a first polarity into said active layer;  
and

a second electrode injecting second type  
10 carriers having a second, opposite polarity into said  
active layer,

said active layer having a composition of  
GaInNP containing therein N as a group V element.

According to the present invention, a large  
15 band discontinuity is guaranteed at the interface  
between the active layer and the first or second  
cladding layer as a result of the use of GaInNP for the  
active layer, and the efficiency of carrier confinement  
is improved substantially. By adjusting the amount of N  
20 in the GaInNP active layer, it becomes possible to set  
the band offset at the interface between the active  
layer and the first or second cladding layer as desired.  
Thereby, the laser diode shows an excellent temperature  
characteristic and operates stably at the room  
25 temperature environment. Further, as a result of the

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1 use of GaInNP for the active layer, the laser diode  
operates in the visible wavelength band including the  
600 nm band. As the active layer of GaInNP is free from  
reactive Al, the growth of the active layer is conducted  
5 easily, without inducing island growth or associated  
problem of deterioration of crystal quality.

Another object of the present invention is to  
provide a vertical-cavity laser diode, comprising:

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10 a substrate having a first conductivity type;  
a first optical reflector provided on said  
substrate;

a first cladding layer having said first  
conductivity type on said first optical reflector in an  
epitaxial relationship with said substrate;

15 an active layer of a group III-V compound  
semiconductor material formed epitaxially on said first  
cladding layer;

a second cladding layer having a second,  
opposite conductivity type on said active layer in an  
20 epitaxial relationship with said active layer;

a second optical reflector provided on said  
second cladding layer;

a first ohmic electrode provided in ohmic  
contact with said substrate; and

25 a second ohmic electrode provided in ohmic



1 contact with said second cladding layer;

said active layer having a composition of GaInNP containing therein N as a group V element.

According to the present invention, an  
5 efficient vertical cavity laser diode operable in the visible wavelength band is obtained. As a result of use of GaInNP for the active layer, a large band discontinuity is guaranteed at the interface between the active layer and the first or second cladding layer, and  
10 the efficiency of carrier confinement is improved substantially. By adjusting the amount of N in the GaInNP active layer, it becomes possible to set the band offset at the interface between the active layer and the first or second cladding layer as desired. Thereby, the  
15 laser diode shows an excellent temperature characteristic and operates stably at the room temperature environment. Further, as a result of the use of GaInNP for the active layer, the laser diode operates in the visible wavelength band including the  
20 600 nm band. As the active layer of GaInNP is free from reactive Al, the growth of the active layer is conducted easily, without inducing island growth or associated problem of deterioration of crystal quality.

Another object of the present invention is to  
25 provide a method of fabricating a compound semiconductor

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1 device, comprising the step of:

(a) forming a first group III-V compound semiconductor layer epitaxially on a substrate;

(b) exposing a surface of said first group  
5 III-V compound semiconductor layer to an atmosphere containing N;

(c) forming, after said step (b), a second group III-V compound semiconductor layer on said first group III-V compound semiconductor layer epitaxially,  
10 said second group III-V compound semiconductor layer containing therein N as a group V element,

wherein said atmosphere is substantially free from a group III element.

According to the present invention, a part of  
15 the atoms constituting the group V element of the first group III-V compound semiconductor layer are replaced with N, and the epitaxial growth of the second group III-V compound semiconductor layer on the first group III-V compound semiconductor layer is facilitated  
20 substantially.

Another object of the present invention is to provide a semiconductor layered structure, comprising:

a first epitaxial layer of AlGaInNP having a composition represented by compositional parameters  $x_1$ ,  
25  $y_1$  and  $z_1$  ( $0 \leq x_1 < 1$ ,  $0 < y_1 \leq 1$ ,  $0 < z_1 < 1$ ) as

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1  $\text{Al}_{x1}\text{Ga}_{y1}\text{In}_{(1-x1-y1)}\text{N}_{z1}\text{P}_{(1-z1)}$ ;

a second epitaxial layer of AlGaInP having a composition represented by compositional parameters  $x2$  and  $y2$  as  $\text{Al}_{x2}\text{Ga}_{y2}\text{In}_{(1-x2-y2)}\text{P}$ , said second epitaxial  
5 layer being disposed adjacent to said first epitaxial layer; and

a third epitaxial layer of AlGaInP having a composition represented by compositional parameters  $x3$  and  $y3$  as  $\text{Al}_{x3}\text{Ga}_{y3}\text{In}_{(1-x3-y3)}\text{P}$ , said third epitaxial  
10 layer being disposed between said first and second epitaxial layers, said first through third epitaxial layers maintaining an epitaxy with each other;

wherein said compositional parameters are set so as to satisfy the relationship:

15  $0 \leq x3 < x2 \leq 1; 0 < y3 \leq 1.$

According to the present invention, the use of AlGaInNP composition, which includes N, for the first layer enables an efficient incorporation of N thereinto as a result of the interaction between Al and N.

20 Thereby, the content of N thus incorporated into the first epitaxial layer can be controlled by controlling the content of Al therein. As a result of the improvement in the efficiency of incorporation of N, the amount of the N-source used in the epitaxial process is  
25 reduced and the cost of forming the layered structure is

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1 reduced. As such a layered structure contains N in the  
first epitaxial layer with a substantial amount, a  
variety of band structures, hitherto not possible, can  
be realized easily.

5 Another object of the present invention is to  
provide a semiconductor light-emitting device,  
comprising:

a substrate of a first conductivity type;  
a first cladding layer of AlGaInP of said  
10 first conductivity type provided on said substrate;  
an active layer of undoped AlGaInNP provided  
on said cladding layer; and

a second cladding layer of AlGaInP of a  
second, opposite conductivity type provided on said  
15 active layer;

said active layer having a composition  
represented by compositional parameters  $x_1$ ,  $y_1$  and  $z_1$  as  
 $Al_{x_1}Ga_{y_1}In_{(1-x_1-y_1)}N_{z_1}P_{(1-z_1)}$  ( $0 \leq x_1 < 1$ ,  $0 < y_1 \leq 1$ ,  $0 <$   
 $z_1 < 1$ ), said first cladding layer having a composition  
20 represented by compositional parameters  $x_2$  and  $y_2$  as  
 $Al_{x_2}Ga_{y_2}In_{(1-x_2-y_2)}P$ ,

wherein there is provided an intermediate  
layer of AlGaInP between said first cladding layer and  
said active layer, said intermediate layer having a  
25 composition represented by compositional parameters  $x_3$ ,

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1      $y_3$  and  $z_3$  as  $Al_{x_3}Ga_{y_3}In_{(1-x_3-y_3)}P$ ,

      said compositional parameters satisfying the  
relationship:

$$0 \leq x_3 < x_2 \leq 1; 0 < y_3 \leq 1.$$

5       According to the present invention, the use of  
AlGaInNP composition, which includes N, for the active  
layer enables an efficient incorporation of N therein to  
as a result of the interaction between Al and N.  
Thereby, the content of N thus incorporated can be  
10    controlled by controlling the content of Al of the  
active layer. As a result of the improvement in the  
efficiency of incorporation of N, the amount of the N-  
source used in the epitaxial process for forming the  
AlGaInNP active layer is reduced and the cost of forming  
15    the layered structure is reduced. By interposing the  
intermediate layer containing minimum amount of Al  
between the first cladding layer and the active layer,  
the segregation of N at the lower boundary of the active  
layer is effectively eliminated, and the quality of the  
20    AlGaInNP crystal constituting the active layer is  
improved. As the active layer contains both Al and N,  
the decrease of the bandgap energy caused by the  
incorporation of N into the active layer is compensated  
for by Al, and the light-emitting device produces a  
25    short optical wavelength radiation. Due to the downward

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1     shifting of the conduction band and valence band as a  
result of incorporation of N into the active layer  
AlGaInNP, there occurs an effective confinement of the  
electrons in the active layer.

5             Another object of the present invention is to  
provide a semiconductor light-emitting device,  
comprising:

              a substrate of a first conductivity type;  
              a first cladding layer said first conductivity  
10     type provided on said substrate;  
              a first optical waveguide layer of undoped  
AlGaInP provided on said first cladding layer;  
              an active layer of undoped AlGaInNP provided  
on said optical waveguide layer;  
15             a second optical waveguide layer of undoped  
AlGaInP provided on said active layer; and  
              a second cladding layer of a second, opposite  
conductivity type provided on said second optical  
waveguide layer

20             said active layer having a composition  
represented by compositional parameters  $x_1$ ,  $y_1$  and  $z_1$  as  
 $Al_{x_1}Ga_{y_1}In_{(1-x_1-y_1)}N_{z_1}P_{(1-z_1)}$  ( $0 \leq x_1 < 1$ ,  $0 < y_1 \leq 1$ ,  $0$   
<  $z_1 < 1$ ), said first optical waveguide layer having a  
composition represented by compositional parameters  $x_2$   
25     and  $y_2$  as  $Al_{x_2}Ga_{y_2}In_{(1-x_2-y_2)}P$ ,

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1           wherein there is provided an intermediate  
layer of AlGaInP between said first optical waveguide  
layer and said active layer, said intermediate layer  
having a composition represented by compositional  
5   parameters  $x_3$  and  $y_3$  as  $\text{Al}_{x_3}\text{Ga}_{y_3}\text{In}_{(1-x_3-y_3)}\text{P}$ ,

          said compositional parameters satisfying the  
relationship

$$0 \leq x_3 < x_2 \leq 1; 0 < y_3 \leq 1.$$

          According to the present invention, the use of  
10   AlGaInNP composition, which includes N, for the active  
layer enables an efficient incorporation of N thereinto  
as a result of the interaction between Al and N.  
Thereby, the content of N thus incorporated can be  
controlled by controlling the content of Al of the  
15   active layer. As a result of the improvement in the  
efficiency of incorporation of N, the amount of the N-  
source used in the epitaxial process for forming the  
AlGaInNP active layer is reduced and the cost of forming  
the layered structure is reduced. By interposing the  
20   intermediate layer containing minimum amount of Al  
between the first optical waveguide layer and the active  
layer, the segregation of N at the lower boundary of the  
active layer is effectively eliminated, and the quality  
of the AlGaInNP crystal constituting the active layer is  
25   improved. As the active layer contains both Al and N,

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1 the decrease of the bandgap energy caused by the  
incorporation of N into the active layer is compensated  
for by Al, and the light-emitting device produces a  
short optical wavelength radiation. Due to the downward  
5 shifting of the conduction band and valence band as a  
result of incorporation of N into the active layer  
AlGaInNP, there occurs an effective confinement of the  
electrons in the active layer.

Another object of the present invention is to  
10 provide a method of fabricating a semiconductor layered  
structure comprising a first epitaxial layer of AlGaInNP  
having a composition represented by compositional  
parameters  $x_1$ ,  $y_1$  and  $z_1$  as  $\text{Al}_{x_1}\text{Ga}_{y_1}\text{In}_{(1-x_1-y_1)}\text{N}_{z_1}\text{P}_{(1-z_1)}$  ( $0 \leq x_1 < 1$ ,  $0 < y_1 \leq 1$ ,  $0 < z_1 < 1$ ), a second  
15 epitaxial layer of AlGaInP having a composition  
represented by compositional parameters  $x_2$  and  $y_2$  as  
 $\text{Al}_{x_2}\text{Ga}_{y_2}\text{In}_{(1-x_2-y_2)}\text{P}$ , said second epitaxial layer being  
disposed adjacent to said first epitaxial layer, and a  
third epitaxial layer of AlGaInP having a composition  
20 represented by compositional parameters  $x_3$  and  $y_3$  as  
 $\text{Al}_{x_3}\text{Ga}_{y_3}\text{In}_{(1-x_3-y_3)}\text{P}$ , said third epitaxial layer being  
disposed between said first and second epitaxial layers,  
said first through third epitaxial layers maintaining an  
epitaxy with each other, said compositional parameters  
25 being set so as to satisfy the relationship ( $0 \leq x_3 < x_2$

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1  $\leq 1; 0 < y_3 \leq 1$ ),

said method comprising the steps of:

forming said first epitaxial layer by using a  
metal organic compound of Al for the source of Al;

5 forming said second epitaxial layer by using a  
metal organic compound of Al for the source of Al; and

forming said third epitaxial layer by using a  
metal organic compound of Al for the source of Al.

According to the present invention, it becomes  
10 possible to control the content of N in the epitaxial  
layers by controlling the Al content thereof. For  
example, it becomes possible to increase the N content  
of the first epitaxial layer by increasing the Al  
content thereof. Further, the quality of the first  
15 epitaxial layer is improved by decreasing or minimizing  
the Al content of the third epitaxial layer, such that  
there occurs no segregation of N at the interface  
between the first epitaxial layer and the third  
epitaxial layer.

20 Other objects and further features of the  
present invention will become apparent from the  
following detailed description of the invention when  
read in conjunction with the attached drawings.

25 BRIEF DESCRIPTION OF THE DRAWINGS

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1           FIG.1 is a diagram explaining a first  
embodiment of the present invention;

          FIG.2 is another diagram explaining the first  
embodiment of the present invention;

5           FIG.3 is a diagram showing the layered  
structure according to a second embodiment of the  
present invention;

          FIG.4 is a diagram showing the PL spectrum of  
the layered structure of FIG.3;

10          FIG.5 is a diagram showing the construction of  
a laser diode according to a third embodiment of the  
present invention;

          FIG.6 is a diagram showing the construction of  
a laser diode according to a fourth embodiment of the  
15       present invention;

          FIG.7 is a diagram showing the band structure  
of the laser diode of FIG.6;

          FIGS.8A and 8B are diagrams showing the  
construction of a laser diode according to a fifth  
20       embodiment of the present invention;

          FIG.9A and 9B are diagrams showing the  
construction of a laser diode according to a sixth  
embodiment of the present invention;

          FIG.10 is a SIMS profile for the structure of  
25       FIG.9B;

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1           FIG.11 is a diagram showing the possible band  
structure of the laser diode of FIG.9B;

          FIG.12 is another diagram showing the band  
structure of the laser diode of FIG.9B;

5           FIG.13 is a diagram showing the construction  
of a laser diode according to a seventh embodiment of  
the present invention;

          FIG.14 is a diagram showing the construction  
of a laser diode according to an eighth embodiment of  
10          the present invention;

          FIG.15 is a diagram showing the construction  
of a laser diode according to a ninth embodiment of the  
present invention;

          FIGS.16A and 16B show the band structure of  
15          the laser diode of FIG.15;

          FIG.17 is a diagram showing the construction  
of an optical disk drive according to a tenth embodiment  
of the present invention;

          FIG.18 is a diagram showing the construction  
20          of an optical transmission system according to an  
eleventh embodiment of the present invention;

          FIGS.19A - 19F are diagrams showing various  
possible band structures for a laser diode according to  
a twelfth embodiment of the present invention;

25          FIGS.20A and 20B are diagrams showing the

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1 effect of strain on the band structure in the laser  
diode of the twelfth embodiment of the present  
invention;

FIG.21 is a diagram showing the construction of a laser diode according to the twelfth embodiment of the present invention;

FIG.22 is a diagram showing the construction of a laser diode according to a thirteenth embodiment of the present invention;

10           FIG.23 is a diagram showing the construction  
of a laser diode according to a fourteenth embodiment of  
the present invention;

FIG.24 is a diagram showing the construction of a laser diode according to a fifteenth embodiment of the present invention;

FIG.25 is a diagram showing a layered structure according to a sixteenth embodiment of the present invention;

FIG.26 is a PL spectrum observed for the  
20 layered structure of FIG.25;

FIG.27 is a SIMS profile observed for the layered structure of FIG.25;

FIG.28 is a diagram showing the construction  
of a laser diode according to a seventeenth embodiment  
25 of the present invention;

1           FIG.29 is a diagram showing the construction  
of a semiconductor layered structure according to an  
eighteenth embodiment of the present invention;

          FIG.30 is a diagram showing the construction  
5 of the semiconductor layered structure of FIG.29 as  
applied to a light-emitting semiconductor device;

          FIG.31 is a diagram showing the effect of Al  
on the incorporation of N into a III-V semiconductor  
layer;

10           FIG.32 is a diagram showing the construction  
of a laser diode according to a nineteenth embodiment of  
the present invention;

          FIG.33 is a diagram showing the construction  
of a laser diode according to a twentieth embodiment of  
15 the present invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

##### [PRINCIPLE]

          The present invention provides an optical  
20 semiconductor device operable in the visible wavelength  
band of 0.6  $\mu\text{m}$  such as 630 nm or 650 nm with high  
efficiency and excellent stability, by using a mixed  
crystal of GaInNP for the active layer in combination  
with a cladding layer of a mixed crystal of AlGaInP.

25           The inventor of the present invention has

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1 previously discovered that the bandgap of an AlGaInP  
mixed crystal is reduced substantially by adding thereto  
a small amount of N as a group V element. The mixed  
crystal thus containing N has a composition represented  
5 as AlGaInNP. Further, such an admixing of N results in  
a decrease of energy both in the conduction band and in  
the valence band, and the efficiency of electron  
confinement in the potential well, formed in the  
conduction band of the AlGaInNP active layer sandwiched  
10 by a pair of AlGaInP cladding layers, is improved  
substantially. While such an addition of N results in a  
formation of a small potential bump in the valence band  
of the AlGaInNP active layer, the problem of formation  
of such a potential bump is easily resolved and the  
15 potential bump is converted to a potential well by  
merely choosing the composition of the AlGaInP cladding  
layers sandwiching the AlGaInNP active layer  
therebetween appropriately. It should be noted that the  
amount of decrease of the energy level caused as a  
20 result of incorporation of N is smaller in the valence  
band than in the conduction band, and there is formed an  
effective potential well both in the conduction band and  
in the valence band. The AlGaInNP active layer further  
has an advantageous feature of lattice matching with the  
25 GaAs substrate due to the effect of N that decreases the

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1 lattice constant of the AlGaInP mixed crystal. Because  
of the large band discontinuity of the potential well  
appearing particularly in the conduction band, the  
electrons are confined effectively in the AlGaInNP  
5 active layer and the laser diode operates stably in the  
room temperature environment.

In order to achieve such a desired relative  
shifting of the conduction band and the valence band in  
the mixed crystal of AlGaInNP, on the other hand, it is  
10 necessary to incorporate N with a concentration of at  
least  $3 \times 10^{19} \text{cm}^{-3}$ . This concentration level of N  
substantially exceeds the concentration level of N  
introduced in an AlGaInP mixed crystal as an impurity  
element forming an isoelectronic trap. It should be  
15 noted that an isoelectronic trap is used commonly for  
converting an AlGaInP mixed crystal to a mixed crystal  
of the direction transition type.

When N is introduced in the AlGaInP mixed  
crystal with such a substantial amount, on the other  
20 hand, there arises a problem in that the quality of the  
resultant AlGaInNP mixed crystal is deteriorated  
substantially. As will be explained later in detail  
with reference to a preferred embodiment, such a  
substantial incorporation of N into a III-V mixed  
25 crystal containing Al invites a substantial formation of

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1 rough surface in the crystal layer of the mixed crystal,  
indicating the cause of the deterioration in the crystal  
quality, while the deterioration of the crystal quality  
facilitates non-optical recombination of carriers and  
5 the efficiency of the laser diode is deteriorated  
inevitably when such a III-V mixed crystal is used for  
the active layer of the laser diode. For example, the  
laser diode may show a large threshold current for laser  
oscillation.

10 On the other hand, the inventor of the present  
invention has newly discovered that there occurs no such  
deterioration in the crystal quality when N is  
introduced into a mixed crystal of GaInP, even in such a  
case in which the concentration of N exceeds the  
15 foregoing concentration level of  $3 \times 10^{19} \text{cm}^{-3}$ . It is  
believed that the exclusion of reactive Al, which tends  
to cause a three-dimensional growth, from the component  
constituting a group III-V mixed crystal contributes to  
the formation of high-quality III-V mixed crystal of  
20 GaInNP.

Further, such an exclusion of Al from the  
component of the group III-V mixed crystal reduces the  
number of the components constituting the III-V mixed  
crystal, while such a reduction in the number of the  
25 components reduces the tendency of immiscibility of the

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1 component elements, which is pertinent to such a multi-  
component mixed crystal system. It should be noted that  
such a III-V mixed crystal containing N generally has a  
composition showing immiscibility and the growth thereof  
5 by an equilibrium process is impossible. Thus, it has  
been necessary to employ a non-equilibrium growth  
process such as an MBE (molecular beam epitaxy) process  
or an MOCVD (metal-organic chemical vapor deposition)  
process in order to grow such a III-V mixed crystal  
10 containing N.

In the present invention, the foregoing  
problems pertinent to the AlGaInNP mixed crystal system  
is avoided successfully by using the GaInNP mixed  
crystal for the active layer of the laser diode.  
15 Thereby, it was discovered that it is preferable to  
increase the concentration of Ga in the mixed crystal,  
as the increased concentration of Ga in the mixed  
crystal also increases the allowable concentration of N  
therein. By increasing the concentration level of N as  
20 such, the energy level of the conduction band of the  
active layer is decreased, and the efficiency of  
electron confinement in the active layer is improved.  
Further, such an increase of the N content in the active  
layer reduces the bandgap of the GaInNP mixed crystal  
25 forming the active layer, while such a reduction of the

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1 bandgap of the active layer contributes to the reduction  
of the oscillation wavelength of the laser diode.  
Thereby, the laser diode successfully operates in the  
visible wavelength including the 600 nm wavelength band.

5 Meanwhile, the inventor of the present  
invention further discovered that the laser diode using  
such a GaInNP active layer shows a poor efficiency when  
the GaInNP active layer is grown directly on an optical  
guide layer or cladding layer of AlGaInNP, in spite of  
10 the fact that the quality of the GaInNP active layer  
itself is improved substantially. The reason of this  
unsatisfactory result is attributed to the existence of  
Al in the underlying optical waveguide layer or cladding  
layer, on which the GaInNP active layer is grown  
15 epitaxially. It is believed that the poor crystal  
quality of the surface of the AlGaInP layer is  
transferred to the active layer grown thereon.

In order to avoid this problem, the present  
invention proposes to separate the active layer of  
20 GaInNP from the cladding layer or optical waveguide  
layer of AlGaInP by using an intermediate layer of a  
group III-V compound semiconductor material that is  
substantially free from Al and N. By interposing such  
an intermediate layer between the GaInNP active layer  
25 and the cladding layer or optical waveguide layer of

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1 AlGaInP, the crystal quality of the active layer is  
improved further, and the efficiency of laser  
oscillation is improved substantially.

5 In order to avoid the unwanted increase of  
laser oscillation wavelength caused as a result of  
interaction of the carriers in the active layer with the  
intermediate layer, it is preferable for form the  
intermediate layer to have a thickness as small as  
possible as compared with the thickness of the GaInNP  
10 active layer but not smaller than a monoatomic layer  
thickness, such that the carriers in the active layer do  
not sense the effect of the potential barrier formed by  
the intermediate layer. As long as the thickness of the  
intermediate layer is sufficiently small, the  
15 perturbation caused in the wavefunction of the carries  
in the GaInNP active layer by the intermediate layer is  
held minimum. Further, in order to avoid the formation  
of a quantum well in the intermediate layer, it is  
preferable that the material of the intermediate layer  
20 forms the type-I heterojunction with the active layer  
rather than the type-II heterojunction. In order to  
improve the quality of the GaInNP active layer, it is  
preferable that the group III-V compound semiconductor  
material forming the intermediate layer is a binary or  
25 ternary compound in the maximum. Further increase in

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1 the number of the constituent elements is  
disadvantageous for securing the necessary quality for  
the GaInNP active layer.

When the laser diode is to be constructed on a  
5 GaAs substrate, the intermediate layer may be formed of  
GaInP. By using GaInP, a lattice matching is guaranteed  
with the cladding layer or optical waveguide layer, and  
the accumulation of strain in the GaInNP active layer is  
controlled relatively easily. Further, the use of  
10 similar component elements for the intermediate layer  
facilitates the growth of the necessary high-quality  
crystal for the active layer. Alternatively, it is also  
possible to use GaP for the intermediate layer, provided  
that the thickness of the GaP intermediate layer is set  
15 smaller than a critical thickness above which misfit  
dislocations are formed. By using GaP for the  
intermediate layer, the optical loss associated with the  
optical absorption in the intermediate layer is  
effectively suppressed as a result of the very large  
20 bandgap of GaP.

When the laser diode is to be constructed on a  
GaP substrate, on the other hand, the intermediate layer  
may be formed of GaInP with a composition having a large  
concentration for Ga. By choosing the composition of  
25 the GaInP intermediate layer to have a high

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1 concentration of Ga, the bandgap of the intermediate  
layer is increased and the lattice constant is reduced  
in conformity with the GaP substrate having a very small  
lattice constant. Thereby, the strain accumulated in  
5 the GaInNP active layer is reduced also as compared with  
the case of forming the laser diode on a GaAs substrate,  
due to the reduced lattice constant of the GaInNP mixed  
crystal caused as a result of admixing of N thereinto.  
By using GaInP for the intermediate layer, it is further  
10 possible to improve the quality of the active layer.

Further, the present invention proposes the  
use of an MQW structure for the active layer of the  
laser diode. Thereby, the MQW is formed as a result of  
a repetitive and alternate stacking of a GaInNP quantum  
15 well layer and a III-V barrier layer which may contain  
Al, wherein the foregoing intermediate layer of GaInP is  
interposed at the interface between the GaInNP quantum  
well layer and the adjacent III-V barrier layer,  
particularly at the interface between the GaInNP quantum  
20 well layer and the underlying barrier layer.

As the GaInP intermediate layer does not have  
a large bandgap comparable to that of the barrier  
layers, the GaInP intermediate layer thus formed  
adjacent to the GaInNP quantum well layer cannot form a  
25 potential barrier defining a quantum well for the GaInNP

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1 quantum well layer. Rather, the GaInP intermediate  
layer tends to form, together with the GaInNP quantum  
well layer, an effectively integral quantum well having  
an increased width. Thereby, it was discovered that the  
5 upper intermediate layer, locating above the GaInNP  
quantum well layer, can be omitted without reducing the  
efficiency of optical emission substantially, although  
such an omission of the upper intermediate layer induces  
a loss of symmetry in the wavefunction of the carriers  
10 confined in the effective quantum well. By omitting the  
upper intermediate layer, the problem of increase of the  
oscillation wavelength of the laser diode, caused as a  
result of increase in the thickness of the effective  
quantum well forming the active part of the laser diode,  
15 is avoided successfully.

[FIRST EMBODIMENT]

In a first embodiment of the present  
invention, a light-emitting semiconductor device having  
20 an active layer of a group III-V compound semiconductor  
material containing therein N and P as a group V element  
is fabricated. More specifically, the active layer of  
the first embodiment thus formed has a composition  
represented as  $\text{Ga}_{x_2}\text{In}_{1-x_2}\text{N}_{z_2}\text{P}_{1-z_2}$  ( $0 \leq x_2 \leq 1$ ,  $0 < z_2 < 1$ ).

25 FIGS.1 and 2 represent the surface of an

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1 AlGaInNP layer and a GaInNP layer formed on a GaAs  
substrate as the active layer of the light-emitting  
semiconductor device by an MOCVD process.

Referring to FIGS.1 and 2, it should be noted  
5 that each of the AlGaInNP layer and the GaInNP layer was  
formed with a thickness of about 1  $\mu\text{m}$ , and the  
deposition of the active layer was made on a crystal  
surface of the GaAs substrate inclined in the  $\langle 011 \rangle$   
direction from the (100) surface by an angle of  $15^\circ$ .  
10 The deposition was made by using TMG (tetramethyl  
gallium), TMA (tetramethyl aluminum), TMI (tetramethyl  
indium) and  $\text{PH}_3$  as respective source of Ga, Al, In and P  
together with a carrier gas of  $\text{H}_2$ . Further, DMHy  
(dimethylhydrazine) was used for the source of N. The  
15 amount of N to be added to the active layer was  
controlled such that any of the AlGaInNP active layer  
and the GaInNP active layer achieves a lattice matching  
with the GaAs substrate. More specifically, the  
composition of the AlGaInNP active layer was set to  
20  $\text{Al}_{0.1}\text{Ga}_{0.5}\text{In}_{0.5}\text{N}_{z2}\text{P}_{1-z2}$  ( $0 < z2 < 1$ ), while the  
composition of the GaInNP active layer was set to  
 $\text{Ga}_{0.5}\text{In}_{0.5}\text{N}_{z1}\text{P}_{1-z1}$  ( $0 < z1 < 1$ ).

From FIGS.1 and 2, it can be seen that the  
AlGaInNP layer of FIG.1 shows a substantial roughness in  
25 the surface morphology thereof, while the GaInNP layer

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1 of FIG.2 shows a mirror flat surface, in spite of the  
fact that the growth of the GaInNP layer of FIG.2 was  
conducted under a disadvantageous condition for  
suppressing the surface roughness. More specifically,  
5 the MOCVD process of growing the GaInNP layer was  
conducted at a lower deposition temperature as compared  
with the case of depositing the AlGaInNP layer of FIG.1  
while supplying simultaneously a larger amount of DMHy.  
In the growth of the GaInNP layer, the ratio of the flow  
10 rate of DMHy to  $\text{PH}_3$  ( $\text{DMHy}/\text{PH}_3$ ) was set seventeen times  
as large as the case of growing the AlGaInNP layer.

As a result of incorporation of such a large  
amount of N without causing a deterioration in the  
quality of the crystal, a shift of photoluminescent  
15 spectrum of as much as 30 nm was observed in the longer  
wavelength side was observed as compared with the case  
in which the active layer contains no substantial amount  
of N. This indicates the decrease of the bandgap energy  
caused as a result of incorporation of N into the active  
20 layer of GaInNP. In the present embodiment, it was  
possible to introduce N successfully with a  
concentration level of  $1 \times 10^{20} \text{cm}^{-3}$ , wherein the amount  
of N thus introduced is equivalent to 0.5 % of the  
entire group V elements.

25 In the case of using AlGaInNP for the active

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1 layer, there arises a problem of poor efficiency of  
optical emission due to the deep level formed the mixed  
crystal of AlGaInNP by Al. Further, the incorporation  
of N further deteriorates the quality of the AlGaInNP  
5 mixed crystal layer. The present invention successfully  
avoids these problems by using GaInNP which is free from  
Al.

[SECOND EMBODIMENT]

10 FIG.3 shows the construction of a  
semiconductor layered structure 10 according to a second  
embodiment of the present invention.

Referring to FIG.3, the semiconductor layered  
structure 10 includes an SQW (single quantum well)  
15 structure formed on a GaAs substrate 11 by an MOCVD  
process, wherein the SQW structure is formed on a buffer  
layer (not shown) of undoped GaAs formed on the GaAs  
substrate 11 epitaxially with a thickness of about 0.2  
 $\mu\text{m}$ . The SQW structure, in turn, includes a barrier  
20 layer 13 of undoped AlGaInP having a composition of  
 $(\text{Al}_{0.5}\text{Ga}_{0.5})_{0.49}\text{In}_{0.51}\text{P}$ , wherein the barrier layer 13 is  
formed on the buffer layer epitaxially with a thickness  
of about 0.2  $\mu\text{m}$ . The barrier layer 13, in turn, is  
covered by an intermediate layer 14 of undoped GaInP  
25 having a composition of  $\text{Ga}_{0.65}\text{In}_{0.35}\text{P}$  and formed

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The active layer 15, in turn, is covered by an intermediate layer 16 of GaInP having a composition similar to that the intermediate layer 14 with a thickness of about 1.2 nm, and a cladding layer 17 of AlGaInP having a composition similar to that of the barrier layer 13 is formed epitaxially on the intermediate layer 16 with a thickness of about 50 nm.

In the structure of FIG.3, it should be noted that both the upper and lower intermediate layers 14 and 15 16 have the thickness of about 1.2 nm, while this thickness corresponds to 2 molecular layers of GaInP. Further, it should be noted that the principal surface of the GaAs substrate 11, on which the structure of FIG.3 is formed, is inclined in the  $\langle 011 \rangle$  direction by 20 an angle of about  $15^\circ$  from the (100) surface. The growth of the layers 13 - 17 is conducted by supplying TMG, TMI, TMA,  $\text{PH}_3$  and  $\text{AsH}_3$  into a reaction chamber of 25 an MOCVD apparatus (not shown) with an appropriate combination, together with a carrier gas of  $\text{H}_2$ . During the growth of the GaInNP quantum well layer 15, DMHy is

1 added to the source gas as a source of N.

It should be noted that the layers 13 and 17  
of AlGaInNP have a large bandgap and act as a barrier  
layer sandwiching therebetween the active layer 15 of  
5 GaInNP as a quantum well layer, wherein each of the  
layers 13 and 17 having the foregoing composition of  
(Al<sub>0.5</sub>Ga<sub>0.5</sub>)<sub>0.49</sub>In<sub>0.51</sub>P achieves a lattice matching with  
the GaAs substrate 11. On the other hand, the  
intermediate layer 14 or 16 of the foregoing composition  
10 (Ga<sub>0.65</sub>In<sub>0.35</sub>P) accumulates therein a tensile strain of  
about 1% when used in combination with the GaAs  
substrate 11. The active layer 15 of GaInNP has the  
composition substantially identical with the composition  
of the GaInP intermediate layer 14 or 16 except that the  
15 active layer 15 further contains N. By increasing the  
Ga content in the GaInNP mixed crystal of the active  
layer 15, the amount of N that can be brought into the  
active layer 15 is increased also. As noted above, the  
active layer 15 has a composition represented as  
20 Ga<sub>0.65</sub>In<sub>0.35</sub>N<sub>0.008</sub>P<sub>0.992</sub>.

FIG.4 shows the PL (photoluminescent) spectrum  
obtained for the structure of FIG.3 in comparison with  
the case in which the intermediate layers 14 and 16 are  
omitted, wherein it should be noted that the curve (a)  
25 of FIG.4 represents the PL spectrum of the structure of

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1 FIG.3, the curve (b) represents the case in which the  
intermediate layers 14 and 16 are omitted from the  
structure of FIG.3, while the curve (c) represents the  
case in which a GaInP mixed crystal free from N is used  
5 for the active layer 15 of FIG.3.

Referring to FIG.4, it can be seen that the PL  
wavelength represented by the curve (a) is shifted in  
the longer wavelength side (665 nm) with respect to the  
curve (c) corresponding to the PL wavelength of 626 nm,  
10 clearly demonstrating the effect of N that decreases the  
bandgap of the GaInP mixed crystal. It should be noted  
that the PL spectrum observed for the curve (a) is clear  
and distinct, indicating that the quality of the GaInNP  
mixed crystal used for the active layer 15 in the  
15 structure of FIG.3 is excellent. In contrast, no PL  
peak was observed when the intermediate layers 14 and 16  
are eliminated.

The result of FIG.4 thus clearly demonstrates  
the effect of the intermediate layers 14 and 16 for  
20 improving the quality of the GaInNP mixed crystal used  
for the active layer 15 in the structure of FIG.3.

In the SQW structure 10 of FIG.3, it is  
further possible to tune the PL wavelength to the  
shorter wavelength side by decreasing the thickness of  
25 the active layer 15 such that there is formed a quantum

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1 well in the active layer 15. The structure of FIG.3 can  
be used for various light-emitting devices and laser  
diodes as will be described hereinafter with reference  
to other embodiments.

5

[THIRD EMBODIMENT]

FIG.5 shows the construction of a stripe laser  
diode 500 according to a third embodiment of the present  
invention based on the layered structure 10 of FIG.3.

10 Referring to FIG.5, the laser diode 500 is  
constructed on a substrate 501 of n-type GaAs having a  
principal surface inclined in the  $\langle 011 \rangle$  direction from  
the (100) surface of GaAs by an angle of about  $15^\circ$  and  
includes a buffer layer 502 of n-type GaAs formed  
15 epitaxially on the foregoing principal surface of the  
substrate 501, wherein the buffer layer 502 carries  
thereon a lower cladding layer 503 of n-type AlGaInP  
formed epitaxially with a composition of  
( $\text{Al}_{0.7}\text{Ga}_{0.3}$ ) $_{0.51}\text{In}_{0.49}\text{P}$ , while the lower cladding layer  
20 503 carries thereon an active layer 504 of undoped  
GaInNP formed also epitaxially with a composition of  
 $\text{Ga}_{0.51}\text{In}_{0.49}\text{N}_{0.01}\text{P}_{0.99}$ , wherein an intermediate layer  
510 of GaP is interposed between the lower cladding  
layer 503 and the active layer 504. The intermediate  
25 layer 510 thus formed has a thickness of about 2

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1     molecular layers, wherein the thickness is smaller than  
a critical thickness above which there occurs a  
formation of misfit dislocations in the intermediate  
layer 510 as a result of lattice misfit with respect to  
5     the GaAs substrate 501. Thereby, the intermediate layer  
510 maintains an epitaxial relationship with the  
underlying AlGaInP cladding layer 503.

On the active layer 504, an upper cladding  
layer 505 of p-type AlGaInP is formed epitaxially with a  
10     composition substantially identical with the composition  
of the lower cladding layer 503 except for the  
conductivity type, wherein another intermediate layer  
511 of GaP is interposed between the active layer 504  
and the upper cladding layer 505 with a thickness  
15     smaller than the foregoing critical thickness. Thereby,  
the intermediate layer 511 maintains an epitaxial  
relationship with the underlying active layer 504.

Further, a contact layer 506 of p-type GaAs is  
formed on the upper cladding layer 505, wherein the  
20     contact layer 506 is covered by an insulating film 507  
of SiO<sub>2</sub> and an upper, p-type electrode 508 of the  
AuZn/Au structure is formed on the insulating film 507  
in ohmic contact with the GaAs contact layer 506 via a  
stripe opening formed in the insulating film 507.  
25     Further, a lower, n-type electrode 509 of the AuGe/Ni/Au

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By injecting holes into the active layer 504 from the top electrode 508 through the stripe opening formed in the insulating film 507, there occurs a stimulated emission in the central part of the active layer 504 as a result of recombination of the holes thus injected with the electrons that are injected from the bottom electrode 509. In the laser diode 500 of the present embodiment, it is of course possible to use a current confinement structure other than the stripe opening formed in the insulating film 507. Further, it

1 is possible to use a strained active layer similar to  
the case of the second embodiment for the active layer  
504 in the laser diode 500, as long as the strained  
active layer has a thickness smaller than the critical  
5 thickness. By straining the active layer, the range  
oscillation wavelength of the laser diode 500 is  
increased, and the laser diode having such a  
construction has an advantageous feature of degree of  
freedom in tuning the laser oscillation wavelength by  
10 inducing a quantum level in the active layer.

In the laser diode 500 of the present  
embodiment, it is possible to use GaAs or InP for the  
intermediate layer 510 or 511 in place of GaP. By using  
GaAs for the intermediate layers 510 and 511, the  
15 intermediate layers 510 and 511 achieve a perfect  
lattice matching with the GaAs substrate 500. In the  
case of using InP for the intermediate layers 510 and  
511, on the other hand, it is necessary to set the  
thickness of the intermediate layers 510 and 511 to be  
20 smaller than a critical thickness above which there  
occurs a development of misfit dislocations in the  
intermediate layers 510 and 511. While it is also  
possible to use other group III-V material for the  
intermediate layers 510 and 511, it is desirable that  
25 the intermediate layers 510 and 511 have a bandgap as

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1 large as possible for avoiding optical loss in the  
active layer 504. The use of GaP noted above is  
particularly advantageous in view of the excellent  
quality of the GaInNP active layer 504 grown on the  
5 intermediate layer 510.

[FOURTH EMBODIMENT]

FIG.6 shows the construction of a stripe laser  
diode 600 according to a fourth embodiment of the  
10 present invention.

Referring to FIG.6, the laser diode 600 is  
constructed on a substrate 601 of n-type GaP carrying  
thereon a buffer layer 602 of n-type GaP, wherein the  
laser diode 600 includes a lower cladding layer 603 of  
15 n-type AlP, and an optical waveguide layer 612 of  
undoped AlGaP having a composition of  $\text{Al}_{0.5}\text{Ga}_{0.5}\text{P}$  is  
grown epitaxially on the lower cladding layer 603.  
Further, the optical waveguide layer 612 is covered by  
an intermediate layer of GaInP having a composition of  
20  $\text{Ga}_{0.7}\text{In}_{0.3}\text{P}$  grown epitaxially on the optical waveguide  
layer 612, and an active layer 604 of GaInNP having a  
composition of  $\text{Ga}_{0.7}\text{In}_{0.3}\text{N}_{0.01}\text{P}_{0.99}$  is formed  
epitaxially on the underlying optical waveguide layer  
612.

25 The active layer 604, in turn, is covered by

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1 an intermediate layer 611 grown epitaxially with a  
composition substantially identical with the  
intermediate layer 612, and the intermediate layer 611  
is covered by an optical waveguide layer 613 grown  
5 epitaxially on the intermediate layer 611 with a  
composition substantially identical with the optical  
waveguide layer 612. The optical waveguide layer 613,  
in turn, is covered by an upper cladding layer 605 of p-  
type AlP grown epitaxially on the optical waveguide  
10 layer 613, and a contact layer 606 of n-type GaP is  
formed further on the cladding layer 605.

The contact layer 606 is covered by an  
insulating film 607 of  $\text{SiO}_2$ , and a p-type electrode 608  
provided on the insulating film 607 achieves an ohmic  
15 contact with the GaP contact layer 606 via a stripe  
opening formed in the insulating film 607. Further, an  
n-type electrode 609 is formed on the bottom surface of  
the GaP substrate 601 in ohmic contact therewith.

It should be noted that the foregoing III-V  
20 semiconductor layers are grown on the GaP substrate 601  
consecutively by an MOCVD process while using the  
gaseous source materials noted before, and there is  
formed a double heterostructure including the active  
layer 604 and the upper and lower cladding layers 603  
25 and 605 as the essential part of the laser diode 600.

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1           In the laser diode 600 having such a  
construction, it should be noted that the active layer  
604 of GaInNP is a material derived from GaInP, while  
GaInP is the direct-transition type semiconductor  
5   material having the largest bandgap. By introducing a  
small amount of N, the GaInNP active layer 604 generally  
achieves a lattice matching with the GaP substrate 601.

          In the laser diode 600 of FIG.6, the  
intermediate layers 610 and 611 are formed of a GaInP  
10   layer having a composition of  $\text{Ga}_{0.7}\text{In}_{0.3}\text{P}$  and a  
thickness of 2 molecular layers, while the intermediate  
layers 610 and 611 may also be formed of GaP. In this  
case, the intermediate layers 610 and 611 achieve an  
ideal lattice matching with the GaP substrate 601.

15           FIG.7 shows the band diagram of the laser  
diode 600 of FIG.6 for the part including the active  
layer 604, intermediate layers 610 and 611 of  
 $\text{Ga}_{0.7}\text{In}_{0.3}\text{P}$ , optical waveguide layers 612 and 613 of  
 $\text{Al}_{0.5}\text{Ga}_{0.5}\text{P}$ , and cladding layers 603 and 605 of AlP.

20           Referring to FIG.7, it can be seen that the  
conduction band  $E_c$  and the valence band  $E_v$  of the active  
layer 604 is shifted in the lower energy side with  
respect to the intermediate layer 610 or 611, causing a  
staggered, type-II heterojunction interface between the  
25   active layer 604 and the intermediate layer 610 or 611.

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1     Thereby, the efficiency of confinement of electrons in  
the potential well formed in the conduction band  $E_c$  in  
correspondence to the active layer 604 is improved.  
Further, it should be noted that there is formed an  
5     effective potential well for the holes in the valence  
band  $E_v$  between the active layer 604 and the cladding  
layer 603 or 605. Thus, an effective confinement of  
holes in the active layer 604 is maintained, and the  
efficiency of the laser diode 600 or the temperature  
10    stability of the operational characteristic thereof is  
improved substantially.

          In the band diagram of FIG.7, it should be  
noted that the magnitude of the foregoing energy shift  
of the active layer 604 is smaller in the valence band  
15     $E_v$  than in the conduction band  $E_c$ , due to the decrease  
of the bandgap of GaInNP caused as a result of  
incorporation of N thereinto.

          As the cladding layer 603 or 605 has a  
refractive index substantially smaller than the  
20    refractive index of the optical waveguide layers 612 and  
613, there occurs also an effective optical confinement  
of photons in the active layer 604 where the stimulated  
emission takes place. The composition of the optical  
waveguide layers 612 and 613 or the composition of the  
25    cladding layers 603 and 605 is of course not limited to

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1 the foregoing combination but any other compositions may  
be used as long as the composition of the optical  
waveguide layers 612 and 613 is represented as  $\text{Al}_{y1}\text{Ga}_{1-y1}\text{P}$  ( $0 \leq y1 < 1$ ) and the composition of the cladding  
5 layers 603 and 604 is represented as  $\text{Al}_{y2}\text{Ga}_{1-y2}\text{P}$  ( $0 \leq y1 < y2 \leq 1$ ).

In the laser diode 600 of FIG.6, the use of  
GaInNP containing N and simultaneously a substantial  
amount of Ga for the active layer 604 reduces the  
10 lattice constant of the active layer 604 and hence the  
compressive stress accumulated therein when combined  
with the substrate 601 of GaP. Note that GaP forming  
the substrate 601 has a very small lattice constant.  
Thus, the laser diode 600 is advantageous for reducing  
15 the laser oscillation wavelength. Further, due to the  
reduced lattice misfit, the active layer 604 grown on  
the Al-free intermediate layer 610 has an excellent  
crystal quality and the efficiency of laser oscillation  
is facilitated further.

20

#### [FIFTH EMBODIMENT]

FIG.8A shows the construction of a laser diode  
700 according to a fifth embodiment of the present  
invention.

25 Referring to FIG.8A, the laser diode 700 is

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1 constructed on a substrate 701 of n-type GaAs having a  
principal surface inclined in the  $\langle 011 \rangle$  direction from  
the (100) surface of GaAs by an angle of about  $15^\circ$  and  
includes a buffer layer 702 of n-type GaAs formed  
5 epitaxially on the foregoing principal surface of the  
substrate 701, wherein the buffer layer 702 carries  
thereon a lower cladding layer 703 of n-type AlGaInP  
formed epitaxially with a composition of  $(\text{Al}_{x_1}\text{Ga}_{1-x_1})\text{In}_{0.49}\text{P}$  ( $0 < x_1 \leq 1$ ), while the lower cladding  
10 layer 703 carries thereon an active layer having an MQW  
structure shown in FIG.8B, wherein an optical waveguide  
layer 712 of n-type AlGaInP having a composition of  
 $(\text{Al}_{x_2}\text{Ga}_{1-x_2})\text{In}_{0.49}\text{P}$  ( $0 < x_2 < x_1 \leq 1$ ) is interposed  
between the lower cladding layer 703 and the MQW  
15 structure constituting the active layer.

On the MQW active layer, there is formed an  
upper cladding layer 705 of p-type AlGaInP epitaxially  
with a composition substantially identical with the  
composition of the lower cladding layer 703 except for  
20 the conductivity type, and another optical waveguide  
layer 713 of p-type AlGaInP is interposed between the  
active layer and the upper cladding layer 705 with a  
composition substantially identical with the composition  
of the lower optical waveguide layer 713.

25 Further, a contact layer 706 of p-type GaAs is

1       formed on the upper cladding layer 705, wherein the  
contact layer 706 is covered by an insulating film 707  
of  $\text{SiO}_2$  and an upper, p-type electrode 708 of the  
AuZn/Au structure is formed on the insulating film 707  
5       in ohmic contact with the GaAs contact layer 706 via a  
stripe opening formed in the insulating film 707.  
Further, a lower, n-type electrode 709 of the AuGe/Ni/Au  
is formed on the bottom surface of the GaAs substrate  
701 in ohmic contact therewith.

10       The foregoing semiconductor layers may be  
formed by an MOCVD process with the gaseous source  
materials used in the preceding embodiments.

FIG.8B shows the MQW structure forming the  
active layer of the laser diode 700.

15       Referring to FIG.8B, the active layer includes  
a repetitive stacking of the structural unit including a  
barrier layer 714 of undoped AlGaInP having a  
composition identical with the composition of the  
AlGaInP cladding layer 712 or 713 except for the  
20       conductivity type and a quantum well layer 704 of an  
undoped GaInNP having a composition of  
 $\text{Ga}_{0.51}\text{In}_{0.49}\text{N}_{0.01}\text{P}_{0.99}$  formed on the barrier layer 714,  
wherein there is interposed an intermediate layer 710,  
711 ... 715 of undoped GaInP having a composition of  
25        $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$  at both upper and lower interface

1 boundaries of each quantum well layer 704.

By interposing the undoped GaInP intermediate layers 710 and 711 at both upper and lower interface boundaries of the quantum well layer 704 constituting the MQW structure as such, an excellent quality is guaranteed for the quantum well layers 704 grown on such GaInP intermediate layers free from Al. In the embodiment of FIG.8B, it should be noted that a further intermediate layer 815 having the composition identical with the composition of the intermediate layer 710 or 711

[SIXTH EMBODIMENT]

FIG.9A shows the construction of a laser diode 800 according to a fifth embodiment of the present invention.

Referring to FIG.9A, the laser diode 800 is constructed on a substrate 801 of n-type GaAs having a principal surface inclined in the  $\langle 011 \rangle$  direction from the (100) surface of GaAs by an angle of about  $15^\circ$  and includes a buffer layer 702 of n-type GaAs formed epitaxially on the foregoing principal surface of the substrate 801, wherein the buffer layer 802 carries thereon a lower cladding layer 803 of n-type AlGaInP formed epitaxially with a composition of  $(Al_{x1}Ga_{1-x1})$

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1  $x_1$ ) $0.51\text{In}_{0.49}\text{P}$  ( $0 < x_1 \leq 1$ ), while the lower cladding  
layer 803 carries thereon an active layer having an MQW  
structure shown in FIG.9B, wherein an optical waveguide  
layer 812 of n-type AlGaInP having a composition of  
5  $(\text{Al}_{x_2}\text{Ga}_{1-x_2})_{0.51}\text{In}_{0.49}\text{P}$  ( $0 < x_2 < x_1 \leq 1$ ) is interposed  
between the lower cladding layer 803 and the MQW  
structure constituting the active layer.

On the MQW active layer, there is formed an upper cladding layer 805 of p-type AlGaInP epitaxially with a composition substantially identical with the composition of the lower cladding layer 803 except for the conductivity type, and another optical waveguide layer 813 of p-type AlGaInP is interposed between the active layer and the upper cladding layer 805 with a composition substantially identical with the composition of the lower optical waveguide layer 813.

Further, a contact layer 806 of p-type GaAs is formed on the upper cladding layer 805, wherein the contact layer 806 is covered by an insulating film 807 of SiO<sub>2</sub> and an upper, p-type electrode 708 of the AuZn/Au structure is formed on the insulating film 807 in ohmic contact with the GaAs contact layer 806 via a stripe opening formed in the insulating film 807. Further, a lower, n-type electrode 809 of the AuGe/Ni/Au is formed on the bottom surface of the GaAs substrate

1 701 in ohmic contact therewith.

The foregoing semiconductor layers may be formed by an MOCVD process with the gaseous source materials used in the preceding embodiments.

5 FIG.9B shows the MQW structure forming the active layer of the laser diode 800.

Referring to FIG.9B, the active layer includes a repetitive stacking of the structural unit including a barrier layer 814 of undoped AlGaInP having a composition identical with the composition of the AlGaInP cladding layer 812 or 813 except for the conductivity type and a quantum well layer 804 of an undoped GaInNP having a composition of  $\text{Ga}_{0.51}\text{In}_{0.49}\text{N}_{0.01}\text{P}_{0.99}$  formed on the barrier layer 814, wherein there is interposed an intermediate layer 810 of undoped GaInP having a composition of  $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$  at a lower interface boundary of each quantum well layer 804.

By interposing the undoped GaInP intermediate layer 810 at both the lower interface boundary of each quantum well layer 804 constituting the MQW structure as such, an excellent quality is guaranteed for the quantum well layers 804 grown on such GaInP intermediate layer 810 free from Al.

FIG.10 shows the SIMS profile for a layered structure in which epitaxial layers of AlGaInP, GaInNP

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1 and AlGaInP are formed consecutively on a GaAs  
substrate, without interposing an intermediate layer of  
GaInP at the upper and lower interface boundaries of the  
GaInNP epitaxial layer.

5 Referring to FIG.10, it can be seen that there  
occurs a remarkable segregation of N at the top surface  
of the AlGaInP epitaxial layer on which the GaInNP  
epitaxial layer is to be formed, while no such a  
segregation of N is observed at the top surface of the  
10 GaInNP epitaxial layer on which the upper AlGaInP  
epitaxial layer is to be formed. It is believed that  
such a segregation of N at the top surface of the lower  
AlGaInP layer is caused as a result of interaction of N  
with the chemically reactive Al contained in the lower  
15 AlGaInP epitaxial layer, while it is believed that such  
an interaction causes the roughing in the top surface of  
the lower AlGaInP epitaxial layer. It should be noted  
that no such a roughing is observed for the top surface  
of the GaInNP epitaxial layer, and the GaInNP epitaxial  
20 layer thus grown has a mirror-flat top surface.

Thus, the MQW structure of FIG.9B, in which  
the intermediate layer of undoped GaInP is interposed  
only at the interface between the bottom surface of the  
GaInNP quantum well layer and the underlying AlGaInP  
25 barrier layer, is still effective for maintaining the

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1     excellent crystal quality for the GaInNP quantum well  
layer. By omitting the upper intermediate layer  
corresponding to the layer 711 of FIG.8B, the effective  
thickness of the quantum well formed by the quantum well  
5     layer 804 is reduced and the oscillation wavelength of  
the laser diode 800 is reduced.

FIG.11 shows the band diagram of the quantum  
well for the case of the laser diode 700 of FIG.7B while  
FIG.12 shows the band diagram of the quantum well for  
10    the laser diode 800 of FIG.8B.

Referring to FIG.11, it can be seen that the  
quantum well layer 704 of GaInNP having a thickness  $d_a$   
forms a staggered, type-II heterojunction interface with  
the intermediate layer 710 or 711 of GaInP, and there is  
15    formed a potential well of electrons in the conduction  
band  $E_c$ . As the thickness  $d_s$  of the intermediate layer  
710 or 711 is very small corresponding to the thickness  
of typically only 2 molecular layers, the effective  
potential well which the electrons in the quantum well  
20    layer 704 sense is relatively wide, having an effective  
well width  $d_0$  generally equal to the sum of the  
thickness  $d_a$  and twice the thickness  $d_s$  ( $d_a + 2d_s$ ), and  
there is formed a quantum state  $E_e$  for the electrons at  
a relatively low energy level in the conduction band  $E_c$ .  
25    Further, there is formed a quantum state  $E_h$  for the

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1 holes in the valence band  $E_v$  at a relatively low energy  
level corresponding to the foregoing effective width  $d_0$   
of the quantum well in the valence band  $E_v$ .

In the band diagram of FIG.11, It should be  
5 noted that the quantum well layer 704 forms a potential  
bump for the holes with respect to the intermediate  
layers 710 and 711 as a result of the formation of the  
staggered type-II heterojunction. Even in such a case,  
there is formed a quantum well for the holes in the  
10 valence band  $E_v$  in correspondence to the quantum well  
layer 704 due to the potential barriers formed by the  
barrier layers 714.

In the band diagram of FIG.12 corresponding to  
the laser diode 800 of FIG.9B, on the other hand, it can  
15 be seen that the band structure becomes asymmetric in  
the direction perpendicular to the epitaxial layers of  
the laser diode 800 due to the elimination of the upper  
intermediate layer corresponding to the layer 711 of  
FIG.11, and the quantum well formed in the conduction  
20 band  $E_c$  has an effective width  $d_1$  generally equal to the  
sum of the thickness  $d_a$  and the thickness  $d_s$  ( $d_a + d_s$ ),  
wherein the effective width  $d_1$  is smaller than the  
effective width  $d_0$  ( $d_1 < d_0$ ). Associated therewith,  
there is formed a quantum state  $E_e'$  for electrons at an  
25 energy level higher than the energy level of the quantum

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1 state  $E_e$ . As the thickness  $d_a$  of the quantum well layer  
804 with respect to the width  $d_1$  of the potential well  
formed in the band structure of FIG.12 is smaller than  
in the case of FIG.11 ( $d_a/d_1 > d_a/d_0$ ), the foregoing  
5 asymmetry of the quantum well potential and associated  
asymmetry of the wavefunction of the carriers confined  
in the potential well is small, and the decrease of  
overlap integral of the carrier probability amplitude  
between the conduction band  $E_c$  and the valence band  $E_v$   
10 is minimized. In view of the fact that quantum states  
are formed at relatively higher energy level in the case  
of the laser oscillation at such a short wavelength, the  
effect of asymmetric potential of the intermediate  
layers does not appear significantly, and the problem of  
15 deterioration of efficiency of carrier recombination and  
associated decrease of efficiency of optical emission at  
the active layer is successfully avoided.

[SEVENTH EMBODIMENT]

20 FIG.13 shows the construction of a vertical-  
cavity laser diode 900 according to a seventh embodiment  
of the present invention, wherein the laser diode 900  
can be regarded as a modification of the laser diode 500  
of the third embodiment described with reference to  
25 FIG.5.

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On the multilayer reflector structure 902 thus  
15 formed, there is formed a lower cladding layer 903 of n-  
type AlGaInP epitaxially with a composition of  
(Al<sub>0.7</sub>Ga<sub>0.3</sub>)<sub>0.5</sub>In<sub>0.6</sub>P, and an intermediate layer 904a of  
undoped GaInP having a composition of Ga<sub>0.6</sub>In<sub>0.4</sub>P is  
formed further on the lower cladding layer 903  
20 epitaxially with a thickness of typically 2 molecular  
layers.

On the intermediate layer 904a thus formed,  
there is formed an active layer 905 of undoped GaInNP  
epitaxially with a composition of  $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.01}\text{P}_{0.99}$ ,  
wherein the active layer 905 carries thereon an

1 intermediate layer 904b of undoped GaInP with a  
composition of  $\text{Ga}_{0.6}\text{In}_{0.4}\text{P}$ , wherein the intermediate  
layer 904b is formed with a thickness of typically 2  
molecular layers.

5 On the intermediate layer 904b, there is  
provided an upper cladding layer 906 of p-type AlGaInP  
epitaxially with a composition substantially identical  
with that of the lower cladding layer 903 except for the  
conductivity type, wherein the upper cladding layer 906  
10 is covered by another intermediate layer 907 of p-type  
GaInP having a composition identical with the  
composition of the intermediate layer 904a or 904b  
except for the conductivity type.

On the intermediate layer 907, a contact layer  
15 908 of p-type GaAs is formed epitaxially, wherein the  
epitaxial layers above the multilayer reflector  
structure 902 are subjected to a patterning process to  
form a generally cylindrical structure having a diameter  
of 10  $\mu\text{m}$  for example and extending in the upward  
20 direction from the top surface of the multilayer  
reflector structure 902.

The side wall of the foregoing cylindrical  
structure and further the exposed top surface of the  
multilayer reflector structure 902 are covered by an  
25 insulation film 910 of  $\text{SiO}_2$  and a p-type electrode 911

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1 having the AuZn/Au structure is formed on the foregoing  
side wall insulation film 910 so as to make an ohmic  
contact with the top surface of the contact layer 908.

5 The p-type electrode 911 and the underlying  
contact layer 908 are then patterned to form a circular  
opening exposing the top surface of the intermediate  
layer 907, and another multilayer reflector structure  
909, formed of alternate stacking of an  $\text{SiO}_2$  layer and a  
10  $\text{TiO}_2$  layer each having a thickness of corresponding to a  
quarter wavelength of the laser oscillation wavelength,  
for example, is provided on the contact layer 908 in  
intimate contact with the exposed top surface of the  
intermediate layer 907. The  $\text{SiO}_2$  layer and the  $\text{TiO}_2$   
layer constituting the multilayer reflector structure  
15 911 may be repeated about 6 times. Further, it should  
be noted that an n-type electrode 912 having the  
AuGe/Ni/Au structure is provided on the bottom surface  
of the substrate 901 in ohmic contact therewith.

20 In the laser diode 900 of FIG.13, the upper  
multilayer reflector structure 909 and the lower  
multilayer reflector structure 902 form together a  
vertical cavity and the laser diode 900 achieves  
stimulated emission of optical radiation at the visible  
wavelength band of 600 nm (0.6  $\mu\text{m}$ ). Thereby, the  
25 optical beam thus produced in the active layer 905 is

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1        amplified as it is reflected back and forth between the  
upper and lower multilayer reflector structures 909 and  
902. The amplified optical beam is then emitted in the  
upward direction as represented in FIG.13 by an arrow.

5            According to the laser diode 900 of the  
present embodiment that uses the active layer 905  
containing therein N as a group V element, it is  
possible to produce a laser beam with the oscillation  
wavelength of 600 nm band with high efficiency and  
10        excellent temperature stability, similarly to the laser  
diodes of the preceding embodiments. In the laser diode  
900 of the present embodiment that uses the composition  
of  $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.01}\text{P}_{0.99}$  for the active layer 905, in  
particular, the laser diode 900 produces the laser beam  
15        at the wavelength of about 680 nm. It should be noted  
that the active layer 905 of the foregoing composition,  
characterized by a lattice constant smaller than the  
lattice constant of GaAs, accumulates therein a tensile  
stress.

20            In the laser diode 900 of the present  
embodiment, it should be noted further that the use of  
the intermediate layer 907 of InGaP containing therein  
no substantial amount of N effectively suppresses the  
roughing of the surface of the layer 907 on which the  
25        upper multilayer reflection structure 909 is formed.

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1     Thereby, the problem of scattering of the optical beam  
at such rough surface and associated decrease of the  
efficiency of laser oscillation is avoided successfully.  
In view of the bandgap energy of the GaInP intermediate  
5     layer 907 larger than the bandgap energy of the GaInNP  
active layer 905, there occurs no substantial absorption  
in the optical radiation produced in the active layer  
905.

10    [EIGHTH EMBODIMENT]

FIG.14 shows the construction of a laser diode  
1000 according to an eighth embodiment of the present  
invention, wherein those parts corresponding to the  
parts described previously are designated by the same  
15   reference numerals and the description thereof will be  
omitted.

In the present embodiment, the multilayer  
reflection structure 902 formed on the n-type GaAs  
active layer 901 in the laser diode 900 is now replaced  
20   by a multilayer reflection structure 1001, wherein the  
multilayer reflection structure 1001 includes alternate  
and repetitive stacking of an n-type AlGaInP epitaxial  
layer having a composition of  $(Al_aGa_{1-a})_{0.5}In_{0.5}P$  ( $0 < a$   
 $\leq 1$ ) and another n-type AlGaInP epitaxial layer having a  
25   composition of  $(Al_bGa_{1-b})_{0.5}In_{0.5}P$  ( $0 \leq b < a$ ), wherein

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1 each of the foregoing first and second AlGaInP epitaxial  
layers is doped with Se and has a thickness  
corresponding to a quarter wavelength of the oscillation  
wavelength of the laser diode 1000.

5 In the laser diode 1000, it should further be  
noted that the active layer 905 of the laser diode 900  
of the previous embodiment is replaced by an active  
layer 1002 of GaInNP, wherein the active layer 1002 has  
a composition of  $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.005}\text{P}_{0.995}$ . The active  
10 layer 905 is vertically sandwiched by the intermediate  
layers 904a and 904b of undoped GaInP similarly to the  
laser diode 900 of the previous embodiment.

The active layer 1002 thus covered by the  
intermediate layer 904b is covered consecutively by a  
15 layer 1003 of p-type InGaP to be described later and the  
contact layer 908 of p-type GaAs, and an upper  
multilayer reflector structure 1005 is formed on the  
GaAs contact layer 908, wherein the multilayer reflector  
structure 1005 contains therein alternate and repetitive  
20 stacking of an undoped AlGaInP epitaxial layer having a  
composition of  $(\text{Al}_a\text{Ga}_{1-a})_{0.5}\text{In}_{0.5}\text{P}$  ( $0 < a \leq 1$ ) and  
another undoped AlGaInP epitaxial layer having a  
composition of  $(\text{Al}_b\text{Ga}_{1-b})_{0.5}\text{In}_{0.5}\text{P}$  ( $0 \leq b < a$ ). It  
should be noted that each of the foregoing first and  
25 second AlGaInP epitaxial layers constituting the

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1 multilayer reflection structure 1005 has a thickness  
corresponding to a quarter wavelength of the oscillation  
wavelength of the laser diode 1000.

Further, the layered structure thus formed is  
5 subjected to a patterning process to form a generally  
cylindrical structure in the upper reflector structure  
1005 such that the cylindrical structure extends in the  
upward direction from the top surface of the contact  
layer 908 with a diameter of about 5  $\mu\text{m}$  for example, and  
10 an ion implantation process of  $\text{H}^+$  is conducted into the  
exposed part of the contact layer 908 to form a high-  
resistivity current confinement region 1006 of a ring-  
shaped form, such that the current confinement region  
1006 surrounds the cylindrical upper reflector structure  
15 1005 with a separation therefrom at the top surface of  
the GaAs contact layer 908 and such that the current  
confinement region 1006 reaches the lower multilayer  
reflector structure 1001 through the active layer 1002.  
Further, the upper p-type electrode 911 is formed on the  
20 top surface of the contact layer 908 in ohmic contact  
therewith at the part where the current confinement  
region 1006 is not formed. Similarly to the laser diode  
900 of FIG.13, the GaAs substrate 901 carries the n-type  
ohmic electrode 912 on the bottom surface thereof.

25 Similarly to the laser diode 900, there is

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1 formed a vertical cavity between the lower reflector  
structure 1001 and the upper reflector structure 1005 in  
the laser diode 1000 of FIG.14, and there occurs a  
stimulated emission in the active layer 1002 as the  
5 optical beam emitted as a result of the recombination of  
carriers in the active layer 1002 is reflected back and  
forth between the lower reflector structure 1001 and the  
upper reflector structure 1005. The optical beam thus  
amplified is emitted in the upward direction as  
10 indicated by arrow in FIG.14. As a result of the  
formation of the ring-shaped current confinement region  
1006, the injection of the carriers occurs in the  
limited area inside the current confinement region 1006,  
and the emission of optical radiation as a result of  
15 recombination of the carriers in the active layer 1002  
occurs efficiently. In view of the composition of the  
GaInNP active layer 1002 of  $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.005}\text{P}_{0.995}$ , the  
oscillation wavelength of the laser diode 1000 of FIG.14  
becomes about 650 nm. Similarly to the laser diodes of  
20 the previous embodiments, the laser diode 1000 of the  
present invention achieves an efficient confinement of  
electrons in the active layer 1002 due to the shift of  
the conduction band  $E_c$  in the lower energy direction  
caused as a result of admixing of N thereto. See the  
25 band diagram of FIG.7. Thereby, the laser diode 1000

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1 maintains the high efficiency of laser oscillation even  
in the room temperature environment.

2 In the laser diode 1000, it should be noted  
3 that the upper reflector structure 1005 can be formed  
4 continuously in the same deposition apparatus without  
5 interrupting the epitaxial process, contrary to the  
6 laser diode 900 of FIG.13. In the case of the laser  
7 diode 900 of FIG.13, it was necessary to interrupt the  
8 epitaxial process and take out the device from the  
9 deposition apparatus for dry etching, before resuming  
10 the deposition of the upper multilayer reflector  
11 structure 909. As the entire semiconductor layers are  
12 formed in the same deposition apparatus without exposure  
13 to the air, there occurs no formation of oxide on the  
14 surface of the epitaxial layers and the upper multilayer  
15 reflector structure 1005 forms the desired vertical  
16 optical cavity, together with the lower multilayer  
17 reflector structure 1001, with a predetermined cavity  
18 length. Thereby, the fabrication process of the desired  
19 vertical cavity laser diode is substantially facilitated  
20 by using the structure of FIG.14.

21 In the laser diode 1000 of FIG.14, it should  
22 be noted that the p-type GaInP layer 1003 has a  
23 composition of  $\text{Ga}_{0.6}\text{In}_{0.4}\text{P}$  and effectively reduces the  
24 spike in the valence band formed in correspondence to  
25

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1 the heterojunction interface between the cladding layer  
906 of p-type AlGaInP and the contact layer 908 of p-  
type GaAs. Thereby, the efficiency of hole injection  
from the upper, p-type electrode 911 is facilitated  
5 substantially. Further, the layer 1003 contributes to  
the diffusion of the holes injected from the electrode  
911 such that the holes are injected uniformly to the  
cylindrical region of the semiconductor layered  
structure defined by the ring-shaped current confinement  
10 region 1006. As the GaInP intermediate layer 1003 has a  
bandgap larger than the bandgap of the GaInNP active  
layer 1002, there occurs no substantial absorption of  
the optical beam produced by the recombination of  
carriers taking place in the active layer 1002. As the  
15 GaInP intermediate layer 1003 of the foregoing  
composition does not achieve a lattice matching with the  
GaAs substrate 901, the thickness of the layer 1003 is  
set to about 10 nm such that the thickness of the layer  
1003 does not exceed the critical thickness thereof.

20 In the laser diode 1000 of FIG.14, it should  
further be noted that the contact layer 908 of p-type  
GaAs absorbs the optical radiation emitted in the active  
layer 1002 of GaInNP as a result of the carrier  
recombination. Thus, the laser diode 1000 reduces the  
25 thickness of the contact layer 908 to about 5 nm so that

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1 the effect of the optical absorption is minimized.

Similarly to the laser diode of the previous  
embodiments, the laser diode 1000 of the present  
embodiment also avoids the deterioration of crystal  
5 quality or laser oscillation efficiency, by sandwiching  
the GaInNP active layer 1002 by the GaInP intermediate  
layers 904a and 904b.

[NINTH EMBODIMENT]

10 FIG.15 shows the construction of a vertical-  
cavity laser diode 1100 according to a ninth embodiment  
of the present invention, wherein those parts  
corresponding to the parts described previously are  
designated by the same reference numerals and the  
15 description thereof will be omitted.

Referring to FIG.15, the laser diode 1100 has  
a construction similar to that of the laser diode 1000  
of FIG.14, except that the lower multilayer reflector  
structure 1001 is replaced with a multilayer reflector  
20 structure 1101 including therein alternate and  
repetitive stacking of a low refractive epitaxial layer  
of n-type and a high refractive epitaxial layer of n-  
type each having a thickness corresponding to a quarter-  
wavelength of the laser oscillation wavelength. It  
25 should be noted that the low refractive layer is

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1 typically formed of  $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$  doped with Se, while the  
high refractive layer is formed of a stacking of a Se-  
doped  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  having a thickness of 4.5 nm a Se-  
doped  $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$  having a thickness of 1.5 nm. The  
5 foregoing high refractive epitaxial layer and the low  
refractive epitaxial layer are repeated about 25 times  
and form a super-lattice structure that constitutes the  
lower reflector structure 1101. Thereby, the super-  
lattice structure thus formed has an effective bandgap  
10 generally corresponding to that of the  $\text{AlGaInP}$  mixed  
crystal having a composition of  $(\text{Al}_{0.1}\text{Ga}_{0.9})_{0.5}\text{In}_{0.5}\text{P}$ .  
Further, the laser diode 1100 of the present embodiment  
uses an upper reflector structure 1105 in place of the  
upper reflector structure 1005 of FIG.14, wherein it  
15 should be noted that the upper reflector structure 1105  
has a similar super-lattice structure except that the  
epitaxial layers are not doped and that the high  
refractive epitaxial layer and the low refractive  
epitaxial layer are repeated 20 times.

20 Further, the laser diode 1100 uses an active  
layer 1103 having an MQW structure in combination with  
an n-type lower cladding layer 1102 of  $\text{AlGaInP}$  and a p-  
type upper cladding layer 1104 both having a composition  
of  $\text{Al}_{0.5}\text{Ga}_{0.5}\text{P}$ . Further, the  $\text{GaInP}$  layer 1003 used in  
25 the laser diode 1000 of FIG.14 is replaced with the

1 GaInP layer 907 of the composition  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ , which is  
used in the laser diode 900 of FIG.13.

FIG.16A shows the band structure of the lower  
multilayer reflector structure 1101 taken in the  
5 direction perpendicular to the epitaxial layers.

Referring to FIG.16A, it can be seen that the  
multilayer reflector structure 1101 includes an  
alternate repetition of a low refractive layer 1201 of  
AlInP doped with Se and having the composition of  
10  $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$  and a high refractive layer 1202 provided  
adjacent to the layer 1201, wherein the high refractive  
layer 1202 is formed of a stacking of a GaInP layer  
having the composition of  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  and doped with Se  
and an AlInP layer doped also with Se and having the  
15 composition of  $\text{Al}_{0.5}\text{In}_{0.5}\text{P}$  as noted previously. The  
GaInP layer has a thickness of 4.5 nm in the high  
refractive layer 1202 while the AlInP has a thickness of  
1.5 nm in the high refractive layer 1202. A similar  
band structure exists also in the upper multilayer  
20 reflector structure 1105 except that the epitaxial  
layers therein are substantially free from doping.

FIG.16B shows the band diagram of the MQW  
structure forming the active layer 1103.

Referring to FIG.16B, the active layer 1103  
25 includes alternate and repetitive stacking of a barrier

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1 layer 1205 of undoped AlInP having the composition of  
Al<sub>0.5</sub>In<sub>0.5</sub>P and a quantum well layer 1204 of undoped  
GaInNP having the composition of Ga<sub>0.5</sub>In<sub>0.5</sub>N<sub>0.005</sub>P<sub>0.995</sub>,  
wherein each of the barrier layer 1205 and the quantum  
5 well layer 1204 has a thickness of 3 nm. Further, it  
should be noted that there is interposed an intermediate  
layer 1203 of undoped GaInP having the composition of  
Ga<sub>0.5</sub>In<sub>0.5</sub>P at the upper and lower surfaces of each  
quantum well layer 1204 in direct and intimate contact  
10 therewith, such that the intermediate layers 1203  
sandwich therebetween the quantum well layer 1204.

As can be seen in the band diagram of FIG.16B,  
the conduction band Ec and the valence band Ev of the  
GaInNP quantum well layer 1204 are shifted in the lower  
15 energy direction with respect to those of the GaInP  
intermediate layer 1203 as a result of the admixing of N  
as a group V element, wherein the quantum well layer  
1204 having such a composition produces an optical  
radiation with the wavelength of 650 nm. As a result of  
20 the shifting of the conduction band Ec for the quantum  
well layer 1204, there occurs an excellent confinement  
of electrons in the quantum well layer and the problem  
of overflowing of thermally excited electrons from the  
quantum well layer is successfully suppressed. Thereby,  
25 the laser diode of the present embodiment provides the

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1 feature of efficient layer oscillation even in the room  
temperature environment.

By using the intermediate layers 1203 in the  
MQW structure of the active layer 1103, epitaxial growth  
5 of a high-quality crystal layer is guaranteed for the  
quantum well layer 1204 that contains N as the group V  
element, even when the quantum well layer 1204 is used  
in combination with the barrier layer 1205 that contains  
Al. Further, the quantum well layer 1204 thus grown on  
10 the Al-free intermediate layer 1203 has a smooth,  
mirror-flat surface.

It should be noted that the foregoing  
formation of the super-lattice structure in the  
multilayer reflector structure 1101 or 1105 or the  
15 formation of the MQW structure 1103 is achieved easily  
by interrupting or switching the supply of the gaseous  
source materials, while such a interruption or switching  
of the source material is conducted by merely  
controlling the valve used for supplying the gaseous  
20 source material in a MOCVD apparatus or the shutter of  
an MBE apparatus.

[TENTH EMBODIMENT]

FIG.17 shows the construction of an optical  
25 disk drive 1300 according to a tenth embodiment of the

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1 present invention.

Referring to FIG.17, the optical disk drive 1300 includes a spindle motor 1309 rotating an optical disk 1308 mounted thereon detachably, wherein the  
5 optical disk drive 1300 further includes a vertical-cavity laser diode 1301 that emits an optical beam in the wavelength band of 0.6  $\mu\text{m}$  in the direction perpendicular to the epitaxial layers forming the laser diode 1301. The laser beam thus emitted is collimated  
10 by a lens 1302 and is directed to a scanning mirror 1304 via an optical beam splitter 1303. The scanning mirror 1304 in turn focuses the laser beam supplied thereto at a desired location of the optical disk 1308 via an objective lens 1305. By driving the scanning mirror  
15 1304, the optical beam spot of the laser beam scans over the recording surface of the optical disk 1308.

Further, the optical disk drive 1300 includes a photodetector 1307 for detecting the laser beam reflected by the optical disk 1308, wherein the laser  
20 beam reflected by the optical disk 1308 is directed to the photodetector 1307 via the optical beam splitter 1303 and a lens 1306.

In the optical disk drive 1300 of the foregoing construction, it is possible to achieve a  
25 reliable read/write operation by using the laser diode

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5 [ELEVENTH EMBODIMENT]

Referring to FIG.18, the optical transmission system 1400 of the present embodiment includes an optical transmitter 1401, wherein the optical transmitter 1401 includes a drive circuit 1402 supplied with an electrical signal and a vertical-cavity laser diode 1403, wherein the vertical-cavity laser diode 1403 is driven by a driving signal produced by the drive circuit 1402 in response to the electrical signal supplied to the drive circuit 1402. Further, it should be noted that the laser diode 1403 is coupled optically to a plastic optical fiber 1404 having a transmission band of 0.6  $\mu\text{m}$  and the optical beam emitted by the laser diode 1403 is effectively injected into the core of the optical fiber 1404.

In the optical transmission system 1400 of the present embodiment, it should be noted the optical transmitter 1401 operates efficiently and with

1 reliability by using any of the vertical cavity laser  
diodes 900 - 1100 described with reference to FIGS.13 -  
15. The use of the laser diodes 900 - 1100 of the  
present invention is particularly preferably in view of  
5 the oscillation wavelength thereof of 0.6  $\mu\text{m}$  band  
coincident to the transmission band of a plastic optical  
fiber.

[TWELFTH EMBODIMENT]

10 As explained previously with reference to the  
band diagram of FIG.7 or with reference to the band  
diagrams of FIGS.11 and 12, the use of the GaInNP layer  
for the active layer in combination with the  
intermediate layer of GaInP causes a shifting in energy  
15 for the conduction band and valence band of the GaInNP  
active layer in the lower energy direction with respect  
to the intermediate layer, and there tends to appear a  
staggered, type-II heterojunction at the interface  
between the intermediate layer and the active layer as  
20 represented in FIG.19A, which is similar to the band  
diagram of FIG.7.

While such a type-II heterojunction may be  
useful for confining electrons in the active layer, such  
a structure is not suitable for confinement of holes in  
25 the active layer. In fact, the holes are not confined

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1 in the active layer as long as the staggered band  
structure of FIG.19A is used, and it has been necessary  
to provide an outer potential well outside the  
intermediate layer of GaInP in the laser diode of  
5 previous embodiments for achieving the confinement of  
the holes necessary for the operation of the laser  
diode. In such a case, however, the overlap integral of  
the carrier wavefunction between the conduction band and  
the valence band is tend to be reduced and the  
10 efficiency of optical radiation of the laser diode is  
tend to be deteriorated. It is desired that the carrier  
confinement occurs in the active layer similarly for the  
electrons and for the holes.

On the other hand, it is known that the band  
15 structure of a III-V compound semiconductor material  
changes when a stress is applied as represented in  
FIG.19B or FIG.19C, wherein it should be noted that  
FIG.19B represents the case in which a compressive  
stress is applied to the material system in which a  
20 GaInNP layer is sandwiched by a pair of GaInP layers,  
while FIG.19C represents the case in which a tensile  
stress is applied to the same material system. In the  
band structure of FIG.19B, it can be seen that the  
valence band  $E_v$  becomes substantially flat at the  
25 heterojunction interface between the GaInP layer and the

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1 GaInNP layer while simultaneously maintaining a large  
band discontinuity in the conduction band  $E_c$  in  
correspondence to the foregoing heterojunction  
interface. In the case of FIG.19C, on the other hand,  
5 the magnitude of band discontinuity at the conduction  
band  $E_c$  is reduced while the bump of the conduction band  
 $E_v$  is not eliminated.

In the laser diode, it is preferable to form a  
type-I heterojunction at the interface between the  
10 GaInNP active layer and the adjacent intermediate layers  
of GaInP as represented in FIG.19D, wherein it should be  
noted that the magnitude of shift of the conduction band  
 $E_c$  or valence band  $E_v$  can be evaluated by the strong  
coupling theory of Harrison according to the  
15 relationship

$$\Delta E_c = -2a\{(c_{11}-c_{12})/c_{11}\}\epsilon, \text{ and}$$

$$\Delta E_v = 2a'\{(c_{11}-c_{12})/c_{11}\}\epsilon + b\{(c_{11}+c_{12})/c_{11}\}\epsilon,$$

20 wherein  $c_{11}$  and  $c_{12}$  represent the lattice constant,  $a$   
represents the hydrostatic deformation potential of the  
conduction band  $E_c$ ,  $a'$  represents the hydrostatic  
deformation potential of the valence band  $E_v$ ,  $b$   
represents an axial deformation potential, while  $\epsilon$   
25 represents a lattice strain. About the strong coupling

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1 theory of Harrison, reference should be made to Appl.  
Phys. Lett. vol.60, no.5, pp.630-632, 1992.

FIG.20A shows the calculated change of the  
valence band energy  $E_v$  and the conduction band energy  $E_c$   
5 under a compressive stress by decreasing the Ga content  
 $x$  below the lattice matching composition of  $x=0.52$ ,  
while FIG.20B shows the change of the valence band  
energy  $E_v$  and the conduction band energy  $E_c$  under a  
tensile stress. In the calculation of FIG.20B, the Ga  
10 content  $x$  is increased beyond the foregoing lattice  
matching composition.

The result of FIGS.20A and 20B indicates that  
the bottom edge of the valence band  $E_v$  can be shifted in  
the direction of higher energy side by increasing the Ga  
15 content  $x$  in the GaInNP active layer. By adjusting the  
amount  $x$  of Ga in the GaInNP active layer, it is  
possible to eliminate the foregoing bump of the valence  
band as represented in the band diagram of FIG.19D. In  
FIG.19D, it should be noted that  $\Delta E_v$  represents the  
20 shift of the valence band energy  $E_v$  caused as a result  
of change in the Ga content  $x$  in the GaInNP mixed  
crystal,  $\Delta E_{\text{strain}}$  represents the foregoing shift of the  
valence band energy  $E_v$  caused as a strain in the GaInNP  
mixed crystal forming the active layer, and  $\Delta E_N$   
25 represents shift of the valence band energy  $E_v$  caused as

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1 a result of incorporation of N in to the GaInNP mixed  
crystal. In order to achieve the foregoing elimination  
of the valence band  $E_v$  in the GaInNP active layer, it is  
necessary that the foregoing relationship holds between  
5 the quantities  $E_N$ ,  $\Delta E_{\text{strain}}$  and  $\Delta E_v$  as

$$\Delta E_N + \Delta E_{\text{strain}} + \Delta E_v > 0.$$

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The band diagram of FIG.19D represents the so-  
10 called type-I heterojunction, which is advantageous for  
efficient recombination of carriers, as both the  
electrons and the holes are accumulated in respective  
potential wells formed in the conduction band  $E_c$  or the  
valence band  $E_v$  of the GaInNP active layer.

15 In FIG.20B, it can be seen that the increase  
of the Ga content  $x$  in the GaInNP layer also causes an  
increase in the conduction band energy  $E_c$ . However, the  
magnitude of shift of the conduction band energy  $E_c$ ,  
caused as a result of increase of the Ga content  $x$   
20 beyond the lattice matching composition, is  
substantially smaller than the foregoing shift  $\Delta E_{\text{strain}}$ ,  
and the effective confinement of the electrons in the  
conduction band is maintained even when the GaInNP  
active layer is thus strained by a tensile stress.

25 FIG.19E shows another principle of modifying

1 the type-II heterojunction of FIG.19A to a type-I  
heterojunction, wherein FIG.19E achieves the desired  
modification of the band structure by introducing a p-  
type dopant into the active layer of GaInNP. As a  
5 result of such a p-type doping, there occurs a relative  
shift of the Fermi level  $E_{fp}$  of the GaInNP active layer  
in the lower energy side with respect to the conduction  
band  $E_c$  or the valence band  $E_v$  thereof, while such a  
relative shift of the Fermi level  $E_{fp}$  in the lower  
10 energy side inside the GaInNP active layer causes, in  
turn, an overall shifting of the conduction band  $E_c$  and  
the valence band  $E_v$  of the active layer in the higher  
energy side with respect to the conduction band  $E_c$  or  
the valence band  $E_v$  of the adjacent GaInP optical  
15 waveguide layer or cladding layer. In the equilibrium  
state, it should be noted that the Fermi energy level  
 $E_{fp}$  of the GaInNP active layer has to coincide with the  
Fermi energy level of the adjacent GaInP optical  
waveguide layer or cladding layer.

20 As a result of such an overall shifting of the  
band diagram of the GaInNP active layer with respect to  
the GaInP optical waveguide layer or cladding layer, the  
type-II heterojunction of FIG.19A is successfully  
modified to the type-I heterojunction represented in  
25 FIG.19E. Thereby, an excellent carrier confinement is

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1 guaranteed in the GaInNP active layer for both the  
electrons and holes, and the efficiency of the laser  
diode is improved.

5 A similar relative shifting of the Fermi  
energy level occurs also when the GaInP intermediate  
layer is doped with an n-type dopant. In the case of  
doping the GaInP intermediate layer by a p-type dopant,  
there occurs a shifting of the Fermi energy level  $E_{fn}$  in  
the higher energy side with respect to the conduction  
10 band  $E_c$  and the valence band  $E_v$ , and the band structure  
of the GaInP intermediate layer thus doped is shifted as  
a whole in the lower energy side with respect to the  
GaInNP active layer, which is now free from doping.  
Thereby, there appears a band structure represented in  
15 FIG.19F, wherein there is formed a type-I heterojunction  
at the interface between the n-type GaInP intermediate  
layer and the undoped GaInNP active layer. In the  
example of FIG.19F, the opposite intermediate layer of  
GaInP is not doped, and there is formed a type-II  
20 heterojunction at the interface between the active layer  
of GaInNP and the intermediate layer of undoped GaInP  
similarly to the case of FIG.19A.

FIG.21 shows the construction of a SCH-type  
laser diode 1500 according to a twelfth embodiment of  
25 the present invention.

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1 Referring to FIG.21, the laser diode 1500 is  
constructed on a substrate 1501 of n-type GaAs covered  
by a buffer layer 1502 of n-type GaAs grown epitaxially  
on the substrate 1501 and includes a lower cladding  
5 layer 1503 of n-type AlGaInP and a lower optical guide  
layer 1504 of undoped AlGaInP, wherein the lower  
cladding layer 1503 and the lower optical waveguide  
layer 1504 are grown epitaxially and consecutively on  
the buffer layer 1502 by an MOCVD process with  
10 respective thicknesses of 1  $\mu\text{m}$  and 0.1  $\mu\text{m}$  and respective  
compositions of  $(\text{Al}_{0.7}\text{Ga}_{0.3})_{0.5}\text{In}_{0.5}\text{P}$  and  
 $(\text{Al}_{0.5}\text{Ga}_{0.5})_{0.5}\text{In}_{0.5}\text{P}$ .

On the lower optical waveguide layer 1504,  
there is formed a lower intermediate layer 1505a of  
15 undoped GaInP having a composition of  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$  with a  
thickness of about 2nm, and an active layer 1506 of  
undoped GaInNP having a composition of  
 $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.01}\text{P}_{0.99}$  is formed further on the lower  
intermediate layer 1505a with a thickness of about 30  
20 nm. Further, an upper intermediate layer 1505b of  
undoped GaInP having a composition substantially the  
same as the composition of the lower intermediate layer  
1505a is formed epitaxially on the active layer 1506  
with a thickness of about 2 nm, and an upper optical  
25 waveguide layer 1507 of undoped AlGaInP having a

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1 composition of  $(\text{Al}_{0.5}\text{Ga}_{0.5})_{0.5}\text{In}_{0.5}\text{P}$  is further formed  
epitaxially on the upper intermediate layer 1505a with a  
thickness of about 0.1  $\mu\text{m}$ .

Further, an upper cladding layer 1508 of n-  
5 type AlGaInP having a composition of  
 $(\text{Al}_{0.7}\text{Ga}_{0.3})_{0.5}\text{In}_{0.5}\text{P}$  is grown epitaxially on the upper  
optical waveguide layer 1507 with a thickness of about 1  
 $\mu\text{m}$ , and a contact layer 1510 of p-type GaAs is formed  
epitaxially on the upper cladding layer 1508 with a  
10 thickness of about 0.5 nm, with an anti-spike layer 1509  
of p-type GaInP having a composition of  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$   
interposed between the upper cladding layer 1508 and the  
contact layer 1510 with a thickness of about 50 nm.

The contact layer 1510 is patterned to form a  
15 stripe pattern extending in the longitudinal direction  
of the laser diode 1500 on the anti-spike layer 1509,  
while the anti-spike layer 1509 is covered, at both  
lateral sides of the contact layer 1510, by a pair of  
insulation patterns 1511 of  $\text{SiO}_2$ . Further, a p-type  
20 electrode 1512 is deposited on the insulation patterns  
1511 including the exposed contact layer 1510, wherein  
the electrode 1512 achieves an ohmic contact with the  
contact layer 1510. Further, an n-type electrode 1513  
is formed on the bottom surface of the substrate 1501 in  
25 ohmic contact therewith.



1           In the laser diode 1500 of the present  
embodiment, it should be noted that the active layer  
1506 contains N and the efficiency of electron  
confinement in the potential well formed in the  
5   conduction band in correspondence to the active layer  
1506 is improved substantially. It should be noted that  
there is formed a band discontinuity of about 80 meV in  
the bottom edge of the conduction band at the interface  
between the active layer 1506 and the adjacent  
10   intermediate layer 1505a or 1505b as a result of  
incorporation of N into the active layer 1506.

On the other hand, such a mere incorporation  
of N into the active layer 1506 leads to the formation  
of the type-II band structure shown in FIG.19A at the  
15   heterojunction interface between the active layer 1506  
and the adjacent intermediate layer 1505a or 1505b as  
noted previously. Thus, the present invention modifies  
the Ga content in the active layer 1506 such that the  
active layer 1506 is no longer satisfies the lattice  
20   matching with respect to the GaAs substrate 1501. More  
specifically, the foregoing composition of  
 $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.01}\text{P}_{0.99}$  for the GaInNP active layer 1506  
causes an accumulation of tensile strain of about 0.6%  
therein, and there occurs a shifting in the valence band  
25   energy  $E_v$  of the GaInNP active layer 1506 in the higher

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$$15 \quad \Delta E_{N^+} \Delta E_{\text{strain}} + \Delta E_v > 0,$$

In the embodiment of FIG.21, it should be noted that the upper and lower intermediate layers 1505a and 1505b have a lattice matching composition with respect to the GaAs substrate 1501. By using the intermediate layers 1505a and 1505b, which are free from

1 N, between the N-containing active layer 1506 and the  
optical waveguide layer 1504 or 1507 that contains Al,  
similarly to the laser diodes of the preceding  
embodiments, the active layer 1506 has an excellent  
5 quality and the efficiency of the laser oscillation is  
improved further.

[THIRTEENTH EMBODIMENT]

FIG.22 shows the construction of an SCH laser  
10 diode 1600 according to a thirteenth embodiment of the  
present invention, wherein those parts corresponding to  
the parts described previously are designated by the  
same reference numerals and the description thereof will  
be omitted.

15 Referring to FIG.22, the laser diode 1600 has  
a construction similar to that of the laser diode 1500  
except that the active layer 1506 of the laser diode  
1500 is now replaced by an active layer 1601 of GaInNP  
having a composition of  $\text{Ga}_{0.45}\text{In}_{0.55}\text{N}_{0.01}\text{P}_{0.99}$ . It  
20 should be noted that the foregoing composition of the  
active layer 1601 is not a lattice matching composition  
with respect to the GaAs substrate 1501 and there is  
introduced a compressive strain of about 0.5%.

In response to the introduction of N, there  
25 occurs a decrease in the bandgap in the GaInNP active

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1 layer 1601 of as much as about 150 meV, wherein it  
should be noted that there further occurs a shift in the  
bottom edge of the valence band  $E_v$  in the lower energy  
side with the magnitude of about 18 meV, similarly to  
5 the embodiment of FIG.21. Thereby, there is formed a  
type-II heterojunction represented in FIG.19A at the  
interface between the active layer 1601 and the adjacent  
intermediate layer 1505a or 1505b, also similarly to the  
embodiment of FIG.21.

10 In the present embodiment, on the other hand,  
the foregoing shift of the bottom edge of the valence  
band  $E_v$  is successfully compensated for by the  
compressive strain of about 0.5%. It should be noted  
that the foregoing compressive strain causes a shift in  
15 the bottom edge of the valence band with a magnitude of  
about 33 meV in the higher energy side at the foregoing  
composition of  $\text{Ga}_{0.45}\text{In}_{0.55}\text{P}$ , as compared with the GaInP  
mixed crystal of the lattice matching composition of  
 $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ . See the relationship of FIG.20A. Thereby,  
20 the valence band  $E_v$  of the GaInNP active layer 1601 is  
located at the higher energy side as compared with the  
valence band  $E_v$  of the adjacent intermediate layer 1505a  
or 1505b.

As the conduction band  $E_c$  of the active layer  
25 1601 is located at the lower energy side with respect to

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1 the conduction band of the intermediate layer 1505a or  
1505b, the type-II heterojunction of FIG.19A is  
successfully modified to the type-I as represented in  
FIG.19D, and the laser diode 1600 oscillates with  
5 excellent efficiency and stability.

[FOURTEENTH EMBODIMENT]

FIG.23 shows the construction of a SCH laser  
diode 1700 according to a fourteenth embodiment of the  
10 present invention, wherein those parts corresponding to  
the parts described previously are designated by the  
same reference numerals and the description thereof will  
be omitted.

Referring to FIG.23, the laser diode 1700 has  
15 a construction similar to that of the laser diode 1500  
except that the active layer 1506 of the laser diode  
1500 is now replaced by an active layer 1701 of GaInNP  
having a lattice matching composition of  
 $\text{Ga}_{0.5}\text{In}_{0.5}\text{N}_{0.01}\text{P}_{0.99}$  and doped to the p-type by Mg with  
20 a concentration level of  $2 \times 10^{18} \text{cm}^{-3}$ . The active layer  
1701 may have a thickness of about 30 nm.

In response to the introduction of N, there  
occurs a decrease in the bandgap in the GaInNP active  
layer 1701 of as much as about 150 meV similarly to the  
25 preceding embodiments. Further, the energy level of the

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1 valence band is shifted in the lower energy side also in  
the active layer 1701, and there is formed a type-II  
heterojunction at the interface between the GaInNP  
active layer 1701 and the adjacent intermediate layer  
5 1505a and 1505b.

In the present embodiment, on the other hand,  
the foregoing shift of the bottom edge of the valence  
band  $E_v$  is successfully compensated for by the overall  
shift of the band structure in the higher energy side  
10 caused for the GaInNP active layer 1701 as a result of  
doping of the same to the p-type, as explained before  
with reference to FIG.19E. As a result of such a  
shifting of the overall band structure including the  
conduction band  $E_c$  and the valence band  $E_v$ , the valence  
15 band  $E_v$  of the GaInNP active layer 1701 is located at  
the higher energy side as compared with the valence band  
 $E_v$  of the adjacent intermediate layer 1505a or 1505b.

As the conduction band  $E_c$  of the active layer  
1701 is located still at the lower energy side with  
20 respect to the conduction band of the intermediate layer  
1505a or 1505b, even after the doping of the active  
layer 1701 to the p-type, the type-II heterojunction of  
FIG.19A is successfully modified to the type-I as  
represented in FIG.19E, and the laser diode 1700  
25 oscillates with excellent efficiency and stability.

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[FIFTEENTH EMBODIMENT]

FIG.24 shows the construction of a SCH laser diode 1800 according to a fourteenth embodiment of the present invention, wherein those parts corresponding to the parts described previously are designated by the same reference numerals and the description thereof will be omitted.

Referring to FIG.24, the laser diode 1800 has a construction similar to that of the laser diode 1500 except that the lower intermediate layer 1505a of the laser diode 1500 is replaced by an intermediate layer 1801 of n-type GaInP having a thickness of 2 nm and doped with Se to a concentration level of  $5 \times 10^{18} \text{cm}^{-3}$  and that the active layer 1506 is replaced by an active layer 1801 of undoped GaInNP having a lattice matching composition of  $\text{Ga}_{0.5}\text{In}_{0.5}\text{N}_{0.01}\text{P}_{0.99}$ . The active layer 1802 may have a thickness of 30 nm.

In the laser diode 1800, too, there occurs a decrease in the bandgap in the GaInNP active layer 1801 in response to the introduction of N thereto, of as much as about 150 meV similarly to the preceding embodiments. Further, the energy level of the valence band is shifted in the lower energy side also in the active layer 1802, and there is formed a type-II heterojunction at the

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1 interface between the GaInNP active layer 1802 and the  
adjacent intermediate layer 1505b.

In the present embodiment, on the other hand,  
the lower intermediate layer 1801 is doped to the n-type  
5 and the band structure of the intermediate layer 1801 is  
shifted in the lower energy side with respect to the  
undoped GaInNP active layer 1802, as explained already  
with reference to FIG.19F.

Thereby, there is formed a type-I  
10 heterojunction at the interface between the active layer  
1802 and the underlying intermediate layer 1801, and  
there occurs an effective blocking of holes injected  
from the p-type electrode 1512 and escaping to the n-  
type GaAs substrate 1501.

15 Thus, the laser diode 1800 of the present  
embodiment is also effective for increasing the  
efficiency of carrier recombination taking place in the  
active layer 1802.

20 [SIXTEENTH EMBODIMENT]

Next, description will be made on an improved  
fabrication process of a group III-V semiconductor  
device such as a laser diode that includes therein a  
III-V semiconductor layer containing N as a group V  
25 element according to a sixteenth embodiment of the

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1 present invention.

In the foregoing embodiments described  
heretofore, the epitaxial growth of the active layer of  
the group III-V compound semiconductor material  
5 containing N as a group V element has been achieved by  
an MOCVD process that uses DMHy as the source of N. As  
such a III-V system containing N as a group V element  
includes a large immiscibility gap therein, the  
epitaxial growth of such a GaInNP active layer is by no  
10 means an obvious matter.

While the inventor of the present invention  
has previously found a successful way to grow such an  
epitaxial layer with controlled amount of N therein, as  
described in the United States patent application  
15 08/917,141 which is incorporated herein as reference,  
there is still a room for improvement.

In the growth of a semiconductor layer on an  
underlying layer or substrate, the nucleation process on  
the underlying layer is generally an important factor.  
20 In the case of the epitaxial growth of a III-V mixed  
crystal layer that includes a large immiscibility gap  
therein, the nucleation process is believed to be a  
critical factor for the successful epitaxial growth.  
However, little investigations have been made so far on  
25 the nucleation process in the III-V system containing N.

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1           During a series of experimental investigations  
of growing a III-V mixed crystal layer containing N as a  
group V element on an underlying layer, the inventor of  
the present invention has discovered that the exposure  
5 of the underlying III-V mixed crystal layer, which is  
free from N, to an atmosphere containing N is effective  
for improving the quality of the desired III-V mixed  
crystal that is grown on such an underlying III-V layer.

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10           More specifically, the inventor of the present  
invention has discovered that exposure of a III-V  
semiconductor layer, which is free from N, to an  
atmosphere containing N induces an exchange of some of  
the atoms of the group V element on the exposed surface  
with N. Thereby, the mixed crystal layer of the desired  
15 III-V semiconductor material containing therein N is  
grown on such a processed surface of the underlying  
layer, without forming defects at the interface between  
the underlying layer and the N-containing epitaxial  
layer grown thereon. It should be noted that any  
20 defects existing on the surface on which an epitaxial  
growth of a next semiconductor layer is to be made, is  
inherited by the next semiconductor layer.

FIG.25 shows the structure of a specimen 1900  
used by the inventor of the present invention for the  
25 foregoing experiments. Hereinafter, the present

1       embodiment will be described with reference to a  
material system that uses an active layer of GaInNAs.

Referring to FIG.25, the specimen 1900 has a  
layered structure formed on an n-type GaAs substrate  
5       1901 and includes a buffer layer 1902 of n-type GaAs  
formed on the substrate 1901 epitaxially, wherein the  
buffer layer 1902 is further covered by an epitaxial  
layer 1903 of n-type AlGaAs with a thickness of about  
0.2  $\mu\text{m}$ .

10       The AlGaAs layer 1903, in turn, is covered by  
an epitaxial layer 1904 of undoped GaAs with a thickness  
of about 0.1  $\mu\text{m}$ , and another epitaxial layer 1905 of  
undoped GaInNAs is formed further on the GaAs layer 1904  
with a thickness of about 7 nm. Thereby, the epitaxial  
15       layer 1905 forms a quantum well. The quantum well layer  
1905 thus formed has a composition set such that the  
quantum well layer 1905 accumulates therein a stress.

On the quantum well layer 1905, there is  
formed another epitaxial layer 1906 of undoped GaAs with  
20       a thickness of about 0.1  $\mu\text{m}$ , and an epitaxial layer 1907  
of p-type AlGaAs is formed further on the epitaxial  
layer 1906.

The layered structure of FIG.25 is formed by  
incorporating the GaAs substrate 1901 into a deposition  
25       chamber of an MOCVD apparatus and supplying various

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1 gaseous source materials into the deposition chamber.

More specifically, the GaAs substrate 1901 is held on a susceptor provided in the deposition chamber, and the growth of the buffer layer 1902 is conducted at the substrate temperature of about 600°C by supplying TMG and AsH<sub>3</sub> into the deposition chamber together with the carrier gas of H<sub>2</sub> as the source materials of Ga and As respectively. After the formation of the buffer layer 1902, a growth of the n-type AlGaAs layer 1903 is conducted while supplying TMA as the source of Al and Si<sub>2</sub>H<sub>6</sub> as the n-type dopant, in addition to TMG and AsH<sub>3</sub>, and the growth of the GaAs layer 1904 is made further on the AlGaAs layer 1903 by supplying TMG and AsH<sub>3</sub>.

After the formation of the GaAs layer 1904, the supply of the source material for the group III elements such as TMG or TMA is interrupted, and the surface of the GaAs layer 1904 is exposed to an atmosphere containing DMHy in addition to AsH<sub>3</sub> while maintaining the substrate temperature to about 600°C, wherein it should be noted that DMHy is used as the source of N in the following process of growing the GaInNAs layer 1905 on the GaAs layer 1904. As a result of such an exposure to the atmosphere containing N, a part of the As atoms on the surface of the GaAs layer 1904 is replaced with N. In other words, the GaAs layer

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1 1904 has a modified surface 1908 having a composition of GaNAs.

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5 After such an exposure of the GaAs layer 1904 to the atmosphere containing N, the growth of the GaInNAs layer 1905 is conducted on the foregoing modified surface 1908 by supplying TMG, TMI, DMHy and AsH<sub>3</sub> respectively as the source materials of Ga, In, N and As. As noted previously, the temperature of the epitaxial growth for the GaInNP layer 1905 is set to  
10 about 600°C, wherein it should be noted that the N content in the layer 1905 is increased when the substrate temperature is reduced or the supply rate of DMHy is increased, or the deposition rate is increased. When the deposition temperature is high, the group V  
15 elements, particularly N, escape easily from the deposited epitaxial layer. Further, it should be noted that the foregoing epitaxial growth of the GaInNAs layer 1905 is restricted by the bottle-neck process of supplying of the group III elements. Thus, whenever the  
20 supply of TMG and TMI is started, the growth of the GaInNAs layer 1905 occurs on the modified surface 1908 of the GaAs layer 1904. As the surface 1908, on which the growth of the GaInNAs layer 1905 occurs, already has the composition of GaNAs, the growth of the GaInNAs  
25 layer 1905 occurs without forming defects at the

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1 interface between the layer 1904 and layer 1905, and the  
GaInNAs layer 1905 is grown with substantially free from  
defects.

5 In the foregoing experiments, the process of  
modifying the surface 1908 of the GaAs layer 1904 was  
conducted by exposing the surface of the GaAs layer 1904  
to the atmosphere containing N for about 30 seconds,  
wherein the atmosphere used for the exposure contained  
DMHy and AsH<sub>3</sub> with the proportion identical with the  
10 atmosphere used for growing the GaInNP layer 1905  
thereon.

FIG.26 shows the PL spectrum observed for the  
specimen of FIG.25 (curve B) in comparison with the PL  
spectrum of a specimen having a similar structure except  
15 that the step of exposure to the N-containing atmosphere  
is omitted (curve A), wherein it should be noted that  
the curve A is represented with a scale ten times as  
large as in the case of curve B.

Referring to FIG.26, it can be seen that the  
20 intensity of the PL spectrum is increased in the case of  
the curve B by the factor of about ten as compared with  
the case of the curve A, clearly indicating the improved  
quality of the GaInNP mixed crystal layer 1905 thus  
grown on the GaNAs surface 1908. As noted already, the  
25 result of FIG.26 of improved crystal quality of the

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1 GaInNAs mixed crystal layer 1905 is believed to be the  
outcome of the improved crystal quality, including the  
effective suppressing of vacant site formation for the  
group V elements, at the foregoing interface 1908  
5 modified to have the composition of GaNAs.

FIG.27 shows the SIMS profile for the  
structure of FIG.25 taken from the top surface of the  
GaAs layer 1906.

Referring to FIG.27, it can be seen that the  
10 GaInNAs layer 1905 is more or less uniformly doped with  
N for substantially the entire thickness thereof. As  
can be seen from FIG.27, the top part of the GaAs layer  
1904 corresponding to the processed surface 1908  
includes a substantial amount of N and in fact has the  
15 composition of GaNAs.

5h A2  
Further, the result of FIG.27 indicates that  
the GaInNAs layer 1905 contains therein a substantial  
amount of C, while the profile of C shows that there  
exists a peak of C concentration in the GaInNAs layer  
20 1905 at the bottom part thereof adjacent to the  
foregoing GaNAs interface 1908. It is believed that the  
C concentration in the GaInNP layer 1905 arises due to  
the methyl group contained in DMHy used for the source  
of N in the growth of the GaInNP layer 1905. The result  
25 of FIG.27 suggests that such an incorporation of C into

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1 the III-V layer occurs inevitably when a part of the  
group V elements is replaced with N in the epitaxial  
growth process of the III-V layer.

It should be noted that the foregoing exposure  
5 process of the GaAs layer 1904 is not limited to 30  
seconds but can be set to any arbitrary duration as long  
as a clear PL intensity is obtained.

[SEVENTEENTH EMBODIMENT]

10 FIG.28 shows the construction of an SQW laser  
diode 2000 having an SCH structure according to a  
seventeenth embodiment of the present invention.

Referring to FIG.28, the laser diode 2000 is  
constructed on a GaAs substrate 2011 and includes a  
15 buffer layer 2012 of the n-type grown epitaxially on the  
GaAs substrate 2011, wherein the buffer layer 2012  
carries thereon a lower cladding layer 2013 of n-type  
AlGaAs grown epitaxially on the buffer layer 2012 with a  
composition of  $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$  and with a thickness of 1.5  
20  $\mu\text{m}$ , and a lower optical waveguide layer 2014 of undoped  
GaAs is formed further on the lower cladding layer 2014  
epitaxially with a thickness of about 120 nm.

It should be noted that the epitaxial layers  
2012 - 2014 are grown on the GaAs substrate 2011  
25 consecutively by an MOCVD process while supplying TMG

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1 and/or TMA as the source of Ga and Al together with AsH<sub>3</sub>  
as a source of As, wherein the surface of the optical  
waveguide layer 2014 thus formed is processed by  
exposing to an atmosphere that contains AsH<sub>3</sub> and DMHy  
5 while maintaining the substrate temperature of about  
600°C for about 60 seconds. During this exposure  
process, the supply of the group III elements is  
suppressed and there occurs no substantial growth of the  
III-V crystal layer on the optical waveguide layer 2014.  
10 As a result of such an exposure to the atmosphere  
containing N and As, a part of the atoms on the surface  
of the layer 2014 is replaced with N as demonstrated in  
the SIMS profile of FIG.27 and there is formed a thin  
layer 2022 of GaNAs on the surface of the optical  
15 waveguide layer 2014. As the atmosphere contains also  
AsH<sub>3</sub>, such an exposure process does not induce formation  
of vacant site for the group V element in the layer  
2022, and the layer 2022 provides an excellent surface  
for further epitaxial growth of a III-V semiconductor  
20 layer thereon.

After such a processing of the surface of the  
GaAs optical waveguide layer 2014 to form the GaNAs  
layer 2022, an epitaxial growth of an active layer 2015  
of undoped GaInNAs layer 2015 is conducted on the layer  
25 2022 by an MOCVD process that uses TMG and TMI for the

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1 source materials of Ga and In and AsH<sub>3</sub> and DMHy as the  
source materials of As and N. Typically, the active  
layer 2015 is formed with a composition of  
Ga<sub>0.8</sub>In<sub>0.2</sub>N<sub>0.02</sub>As<sub>0.98</sub> and has a thickness of about 10  
5 nm. Thereby, the active layer forms a quantum well  
characterized by quantum levels formed therein for  
electrons and holes. It should be noted that the active  
layer 2015 having such a composition accumulates therein  
a compressive strain of about 1%. Thereby, there is  
10 formed a type-I heterojunction at the interface between  
the GaInNAs active layer 2015 and the underlying GaAs  
optical waveguide layer 2014.

On the active layer 2015 thus formed, there is  
formed an upper optical waveguide layer 2016 of undoped  
15 GaAs epitaxially with a thickness of about 120 nm, and  
an upper cladding layer of p-type AlGaAs having a  
composition of Al<sub>0.4</sub>Ga<sub>0.6</sub>As is formed further on the  
upper optical waveguide layer 2016 epitaxially with a  
thickness of about 1.6 μm.

20 On the upper cladding layer 2017, there is  
formed a contact layer 2018 of p-type GaAs epitaxially  
with a thickness of about 0.3 μm, and an insulating film  
2020 of SiO<sub>2</sub> is formed on the contact layer 2018. The  
contact layer 2018 is formed with a stripe opening  
25 extending in the longitudinal direction of the laser

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1 diode, and a p-type electrode 2019 is formed on the  
insulating film 2020 in ohmic contact with the GaAs  
contact layer 2018 at the stripe opening in the  
insulating film 2020. Further, an n-type electrode 2021  
5 is provided on the bottom surface of the substrate 2011  
in ohmic contact therewith.

In the laser diode 2000 of FIG.28, it should  
be noted that the active layer 2015 of GaInNAs forming  
the SQW structure has an excellent quality for the  
10 crystal and the optical loss caused by non-optical  
recombination of the carriers is minimized. As a result  
of use the active layer 2015 of GaInNAs containing N  
therein, a large band discontinuity is guaranteed in the  
conduction band at the heterojunction interface to the  
15 underlying GaAs optical waveguide layer 2014 or the  
overlying GaAs optical waveguide layer 2016, there  
occurs an effective confinement of electrons in the  
active layer 2015 and the preferable feature of high  
efficiency of laser oscillation is maintained even when  
20 the laser diode 2000 is operated in the room temperature  
environment. The laser diode 2000 of the present  
embodiment produces an optical beam with the optical  
wavelength band of 1.3  $\mu\text{m}$ .

In the present embodiment, it should be noted  
25 that the deposition process of the epitaxial layers 2012

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1     - 2018 is by no means limited to the MOCVD process  
described but an MBE process may be used similarly.  
Further, the active layer 2015 is by no means limited to  
have the SQW structure but may have an MQW structure.

5

[EIGHTEENTH EMBODIMENT]

FIG.29 shows a semiconductor layered structure  
according to an eighteenth embodiment.

As explained with reference to FIG.10, there  
10 occurs a remarkable concentration or segregation of N  
when a GaInP layer is grown epitaxially on an underlying  
AlGaInP layer by an MOCVD process, indicating that there  
exists a strong interaction between Al in the AlGaInP  
layer and N that is supplied to the surface of the  
15 AlGaInP layer together with other source elements of the  
GaInP layer.

The result of FIG.10 thus indicates that the  
content of N to be incorporated into the III-V epitaxial  
layer can be increased significantly when Al is  
20 incorporated into the III-V epitaxial layer as the group  
III element. Due to the increased content of N, the  
degree of freedom for designing the band structure of  
the III-V epitaxial layer is increased substantially,  
and various band structures that have not been realized  
25 hitherto may be obtained.

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1 Referring to FIG.29, it can be seen that there  
is provided an epitaxial layer 2111 of AlGaInP, on which  
an epitaxial layer 2102 of AlGaInP and an epitaxial  
layer 2101 of AlGaInNP are deposited epitaxially and  
5 consecutively, wherein the epitaxial layer 2101 has a  
composition represented by the compositional parameters  
 $x_1$ ,  $y_1$  and  $z_1$  as  $\text{Al}_{x_1}\text{Ga}_{y_1}\text{In}_{(1-x_1-y_1)}\text{N}_{z_1}\text{P}_{(1-z_1)}$ , the  
epitaxial layer 2111 has a composition represented by  
the compositional parameters  $x_2$  and  $y_2$  as  $\text{Al}_{x_2}\text{Ga}_{y_2}\text{In}_{(1-x_2-y_2)}\text{P}$ , and the epitaxial layer 2102 has a composition  
10 represented by the compositional parameters  $x_3$  and  $y_3$  as  
 $\text{Al}_{x_3}\text{Ga}_{y_3}\text{In}_{(1-x_3-y_3)}\text{P}$ , in which the compositional  
parameters are set so as to satisfy the relationship  $0 \leq$   
 $x_1 < 1$ ,  $0 \leq x_3 < x_2$ ,  $0 < y_1 \leq 1$ ,  $0 \leq y_2 < 1$ ,  $0 < y_3 \leq 1$ ,  
15 and  $0 < z_1 < 1$ .

Further, the epitaxial layer 2102 is provided  
on the epitaxial layer 2101, and an epitaxial layer 2103  
having a composition identical with that of the  
epitaxial layer 2111 is provided on the epitaxial layer  
20 2101.

In the construction of FIG.29, the energy  
level of both of the conduction band and valence band is  
decreased in the AlGaInNP epitaxial layer 2101 as a  
result of incorporation of N as explained before.  
25 Thereby, it should be noted that the amount of N to be

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1 incorporated in the epitaxial layer 2101 is increased  
significantly due to the presence of Al in the epitaxial  
layer 2101, and the degree of freedom of band structure  
designing is increased substantially. Further, in view  
5 of the improved efficiency of incorporating N into the  
epitaxial layer 2101, only a small amount of N source is  
used for causing a substantial modification of the band  
structure of the layer 2101. Thereby, the cost of  
forming the semiconductor layered structure of FIG.29 is  
10 reduced also.

As noted already with reference to FIG.10, the  
existence of Al in the layer underlying the layer that  
contains N causes a severe deterioration in the quality  
of the N-containing layer grown thereon due to the  
15 segregation of N at the interface between the N-  
containing layer and the underlying layer. Thus, in the  
structure of FIG.29, the Al content x3 of the layer 2102  
underlying the AlGaInNP layer 2101 is reduced  
substantially as compared with the Al content x2 of the  
20 epitaxial layer 2111 further underlying the layer 2102.  
The Al content x3 of the layer 2102 may be zero as well.  
Thereby, the segregation of N at the interface between  
the AlGaInNP layer 2101 and the underlying layer 2102 is  
successfully suppressed and the AlGaInNP layer 2101 can  
25 be grown with an excellent quality. Further, by

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1 interposing such an intermediate layer 2102 between the  
epitaxial layer 2111 of AlGaInP and the AlGaInNP layer  
2101, it becomes possible to increase the Al content x2  
without problem. By increasing the Al content x2, the  
5 bandgap of the layer 2111 is increased substantially.  
It should be noted that the intermediate layer 2102 may  
have small thickness just enough for covering the  
surface of the layer 2111.

FIG.30 shows the layered structure of FIG.29  
10 in more detail, wherein FIG.30 shows the layered  
structure as applied to a light-emitting device.

Referring to FIG.30, the layered structure of  
FIG.29 is constructed on a GaAs substrate 2105 covered  
by a buffer layer 2104 of GaAs, wherein an AlGaInP layer  
15 2111a having a thickness of 0.1  $\mu\text{m}$  and a composition of  
(Al<sub>0.5</sub>Ga<sub>0.5</sub>)<sub>0.5</sub>In<sub>0.5</sub>P is formed epitaxially on the  
buffer layer 2104 in correspondence to the layer 2111 of  
FIG.29 as a lower cladding layer, an intermediate layer  
2102a of AlGaInP having a thickness of 4 nm and a  
20 composition of (Al<sub>0.1</sub>Ga<sub>0.9</sub>)<sub>0.5</sub>In<sub>0.5</sub>P is formed  
epitaxially on the AlGaInP layer 2111a in correspondence  
to the layer 2102 of FIG.29, and the AlGaInNP layer 2101  
having a thickness of 30 nm and a composition of  
(Al<sub>0.2</sub>Ga<sub>0.8</sub>)<sub>0.5</sub>In<sub>0.5</sub>N<sub>0.002</sub>P<sub>0.998</sub> is formed on the  
25 intermediate layer 2102a in correspondence to the

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1 AlGaInNP layer 2101 of FIG.29. On the AlGaInNP layer  
2101, there is formed an AlGaInP intermediate layer  
2102b substantially identically with the intermediate  
layer 2102a, and an AlGaInP layer 2103b is formed  
5 further on the AlGaInP intermediate layer 2102b  
similarly to the intermediate layer 2103a as an upper  
cladding layer.

In the structure of FIG.30, a semi-insulating  
GaAs single-crystal having a surface inclined with  
10 respect to the (100) surface in the  $\langle 011 \rangle$  direction with  
an angle of about  $15^\circ$  is used for the GaAs substrate  
2105. The structure of FIG.30 is typically formed by an  
MOCVD process while using TMG for the metal organic  
source of Ga, TMA for the metal organic source of Al,  
15 TMI for the metal organic source of In,  $\text{PH}_3$  as the  
gaseous source of P, and DMHy as the organic source of  
N, together with a carrier gas of  $\text{H}_2$ , wherein the  
deposition of the epitaxial layers is typically  
conducted at a temperature of about  $750^\circ\text{C}$ , which is  
20 substantially higher than the conventional temperature  
used for growing an N-containing III-V layer of about  
 $650^\circ\text{C}$ . In the foregoing growth process, it is also  
possible to use MMHy (monomethylhydrazine) for the  
organic source of N.

25 FIG.31 compares the amount of N incorporated

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1 into an AlGaInP epitaxial layer having a composition of  
(Al<sub>0.2</sub>Ga<sub>0.8</sub>)<sub>0.5</sub>In<sub>0.5</sub>P in comparison with the case of a  
GaInP epitaxial layer having a composition of  
Ga<sub>0.5</sub>In<sub>0.5</sub>P.

5 Referring to FIG.31, it can be seen that the  
amount of N incorporated into the GaInP epitaxial layer  
increases with increasing mole ratio of DMHy with  
respect to PH<sub>3</sub> defined as [DMHy]/([PH<sub>3</sub>] + [DMHy]).  
Further, there is a tendency that the amount of N thus  
10 incorporated increases with decreasing deposition  
temperature of the GaInP epitaxial layer.

On the other hand, FIG.31 also represents a  
remarkable result in that, when Al is contained in the  
epitaxial layer, the amount of N thus incorporated  
15 increases sharply even in the case the mole ratio of  
DMHy is as low as about 1%. This result is in good  
agreement with the result of FIG.10 indicating the  
segregation of N at the interface between the AlGaInP  
layer and the GaInNP layer grown thereon.

20 In the structure of FIG.31, it should be noted  
that the quality of the AlGaInNP epitaxial layer 2101  
would be deteriorated substantially when the  
intermediate layer 2102a is omitted, because of  
extensive formation of rough surface. However, this  
25 problem is successfully avoided by interposing the

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1 intermediate layer 2102a with a reduced or zero Al-  
content, and the AlGaInNP epitaxial layer 2101 thus  
grown on the intermediate layer 2102a shows a mirror  
flat top surface. As noted already, the thickness of  
5 the intermediate layer 2102a can be very small such as 4  
nm as noted above, as long as the intermediate layer  
2102a covers the top surface of the underlying AlGaInP  
cladding layer 2111a uniformly.

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The light-emitting device of FIG.30 is driven  
10 by injecting electrons and holes into the AlGaInNP  
active layer 2101a respectively from the lower cladding  
layer 2111a and the upper cladding layer 2103b and shows  
a PL wavelength offset in the longer wavelength  
direction due to the incorporation of N in the active  
15 layer 2101a. Because of the mirror flat surface  
achieved for the intermediate layer 2102a and the active  
layer 2101a, the light-emitting device of FIG.30  
achieves a high efficiency of light emission.

Further, because of the large band  
20 discontinuity in the conduction band at the interface  
between the active layer and the adjacent intermediate  
layer 2102a or 2102b and thus the adjacent cladding  
layer 2111a or 2103b, the overflowing of carriers from  
the active layer 2101 is effectively minimized and the  
25 efficiency of light emission is improved substantially,

1 similarly to the previous embodiments due to the  
incorporation of N into the active layer 2101.

Further, the light-emitting device of FIG.30  
can decrease the optical wavelength while simultaneously  
5 maintaining the large band discontinuity, by  
incorporating Al and N simultaneously into the active  
layer 2101. It should be noted that N causes a downward  
shifting of the conduction band energy and valence band  
energy and further the decrease of the bandgap energy,  
10 while Al compensates for the decrease of the bandgap  
energy. Thereby, the light-emitting device of FIG.30  
produces a short wavelength optical beam with a high  
efficiency of emission.

It should be noted that the structure of  
15 FIG.29 or 30 can be formed also by an MBE process.  
Further, the source of N is not limited to DMHy but  
other N-containing compounds such as  $\text{NH}_3$  may also be  
used.

20 [NINETEENTH EMBODIMENT]

FIG.32 shows the construction of an edge-  
emission-type stripe laser diode according to a  
nineteenth embodiment of the present invention in a  
cross-sectional view as viewed in an axial direction.

25 Referring to FIG.32, the laser diode is

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1 constructed on a substrate 2310 of n-type GaAs having an  
inclined surface similar to the one described with  
reference to FIG.29, and includes a lower cladding layer  
2308 of n-type AlGaInP having a thickness of 1  $\mu\text{m}$  and a  
5 composition of  $(\text{Al}_{0.7}\text{Ga}_{0.3})_{0.5}\text{In}_{0.5}\text{P}$  formed on the GaAs  
substrate 2310, a lower optical waveguide layer of  
undoped AlGaInP having a thickness of 0.1  $\mu\text{m}$  and a  
composition of  $(\text{Al}_{0.5}\text{Ga}_{0.5})_{0.5}\text{In}_{0.5}\text{P}$  formed on the lower  
cladding layer 2308, and a lower intermediate layer  
10 2302a of undoped AlGaInP having a thickness of 4 nm and  
a composition of  $(\text{Al}_{0.1}\text{Ga}_{0.9})_{0.5}\text{In}_{0.5}\text{P}$  formed on the  
lower optical waveguide layer 2311, and an active layer  
2301 of undoped AlGaInNP having a composition of  
 $(\text{Al}_{0.2}\text{Ga}_{0.8})_{0.5}\text{In}_{0.5}\text{N}_{0.002}\text{P}_{0.998}$  is formed on the lower  
15 intermediate layer 2302a with a thickness of about 30  
nm.

Further, on the active layer 2301, there is  
formed an upper intermediate layer 2302b of undoped  
AlGaInP with composition and thickness similar to those  
20 of the lower intermediate layer 2302a, and an upper  
optical waveguide layer 2303 of undoped AlGaInP is  
formed further on the upper intermediate layer 2302b  
with thickness and composition similar to those of the  
lower optical waveguide layer 2311. On the upper  
25 optical waveguide layer 2303, there is formed an upper

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1 cladding layer 2304 of p-type AlGaInP with composition  
and thickness similar to those of the lower cladding  
layer 2308 except for the conductivity type, and a  
contact layer 2305 of p-type GaAs is formed further on  
5 the upper cladding layer 2304.

The GaAs contact layer 2305 is covered with an  
SiO<sub>2</sub> film 2306 having a contact window exposing the  
contact layer 2306, and a p-type electrode 2307 is  
provided on the SiO<sub>2</sub> film 2306 in contact with the  
10 contact layer 2306 at the contact window. Further, an  
n-type electrode 2310 is provided on the bottom surface  
of the substrate 2309.

In the structure of FIG.32, it should be noted  
that the optical waveguide layer 2311 corresponds to the  
15 epitaxial layer 2111 of FIG.29, the intermediate layer  
2302a corresponds to the epitaxial layer 2102 of FIG.29,  
the active layer 2101 corresponds to the epitaxial layer  
2101 of FIG.29, the intermediate layer 2102 corresponds  
to the epitaxial layer 2102 of FIG.29, and the optical  
20 waveguide layer 2303 corresponds to the epitaxial layer  
2103 of FIG.29.

The laser diode of FIG.32 has an advantageous  
feature of effective electron confinement in the active  
layer 2301 and simultaneously an advantageous feature of  
25 increased bandgap energy for emitting a short wavelength

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1 laser beam as a result of simultaneous incorporation of  
Al and N into the active layer 2301.

[TWENTIETH EMBODIMENT]

5 FIG.33 shows the construction of an edge-  
emission-type stripe laser diode according to a  
twentieth embodiment of the present invention in an  
axial cross-sectional view, wherein those parts  
corresponding to the parts described previously are  
10 designated by the same reference numerals and the  
description thereof will be omitted.

Referring to FIG.33, the laser diode of the  
present embodiment has a construction similar to that of  
FIG.32, except that undoped InGaP layers 2302c and 2302d  
15 having a composition of  $\text{Ga}_{0.65}\text{In}_{0.35}\text{P}$  are used in place  
of the AlGaInP intermediate layers 2302a and 2302b. By  
using the composition entirely free from Al for the  
intermediate layers 2302c and 2302d, the quality of the  
N-containing active layer 2301 is improved and the  
20 efficiency of laser oscillation is also improved.

While the present embodiment is explained with  
reference to a material system that uses GaInNP for the  
active layer, it should be noted that a similar result  
is obtained also for other systems that uses other N-  
25 containing III-V material such as GaInNAs for the active

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1 layer. In this case, a photon emission in the optical  
wavelength band of 1.3  $\mu\text{m}$  becomes possible.

Further, the present invention is not limited  
to those embodiments described heretofore, but various  
5 variations and modifications may be made without  
departing from the scope of the invention.

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